Decarbonisation of Aluminium Production by Demand Side Response

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Abstract

Many smelters in future will need to reduce their dependence on baseload power generation and increase their usage of renewable energy, to create lower emission products, and assist decarbonization of global power grids. One pathway to do this is power modulation, to align smelter power consumption with variable energy availability. The retrofittable EnPot technology can enable +/-20 % modulation at any time, while maintaining cell heat balance, or larger modulations for extended periods. Decarbonizing the power system provides by far the greatest driver to reduce the carbon footprint of aluminium and firming of Variable Renewable Energy (VRE) via smelter modulation is the cheapest way to achieve this, thereby attracting governmental attention and potential funding. A detailed energy market analysis shows that beyond the decarbonization benefits, modulation is also economically advantageous, and opens the door to several ways of sharing the value of lower energy prices between smelters, generators, and grid operators.

Keywords: Power modulation, Emissions, Decarbonization, Heat transfer, Energy.

1. Introduction

Heat balance control allows the smelter power usage to be modulated significantly both upwards and downwards, where previously almost constant power loads have been required. Being able to vary loads will make aluminium smelters much more compatible with future power grids featuring more variable renewable energy (VRE), as well as providing valuable services to support more renewable grids. Because power generation is by far the largest component of the aluminium industry's CO_2 emissions, enabling the transition away from power generation via fossil fuels is the single most significant way to accelerate the decarbonization of aluminium smelting as we know it today.

2. EnPot Technology

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. The key feature of EnPot technology is the patented shell heat exchanger (SHE) units which cover the upper sidewall of each smelting cell and are connected to a duct network with suction fans (Figure 1). The airflow through the system can be varied, such that high airflow gives significantly increased heat transfer from the sidewalls, while lower airflow, below a base demand, results in cell insulation [1,2].
Power modulation in a smelter means increasing or decreasing line amperage. At higher amperage cells need to shed more heat while at lower amperages it is necessary to retain more heat in the process. The cooling and insulation capability of EnPot enables smelters to modulate their power usage by approximately ±20 % at any time, for any duration, where the heat balance

of the pots is always maintained. Larger modulations of up to ±30 % are also possible when coupled with other process changes such as anode cover thickness, or pot suction draught rates, which may take approximately one month (one anode cycle) to practically implement, and so cannot be used spontaneously. The insulating ability of EnPot furthermore allows full shutdown of potlines for approximately twice the duration that can be achieved naturally, while allowing safe restart of pots afterwards, as well as enhanced protection at times of unexpected power loss.

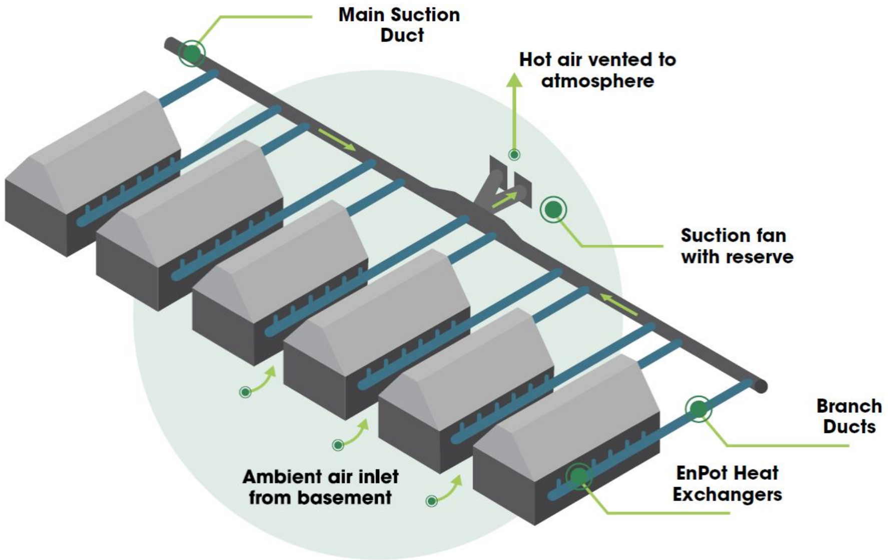

Figure 1. Ducted network for a section of aluminium smelting cells with installed EnPot heat exchangers.

3. Aluminium Decarbonisation

The aluminium smelting process emitted an average of 12.3 tonnes of CO_2-equivalent emissions from per tonne of primary aluminium globally in 2019. This includes 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 much larger Scope 2 component occurs because of the carbon-intensive sources of power used worldwide for aluminium production, largely consisting of coal (64 %) and gas (10 %) powered generation, with only 27 % of production from low-carbon sources such as hydro [5].

Previous articles have investigated possible pathways for the global smelting industry to decarbonize and reach 'net zero' by 2050 [3, 10], utilizing key technologies including inert anodes, energy efficiency improvements, and avoiding scope 2 emissions by changing the sources of energy generation. Figure 2 shows a 'high growth' scenario of 3.8 % annual production increases until 2050, and the relative impacts of these technologies to reach net zero carbon. Decarbonisation of the power system, by reduction of Scope 2 emissions, is clearly the much larger and more pressing aspect when compared with Scope 1 reductions.

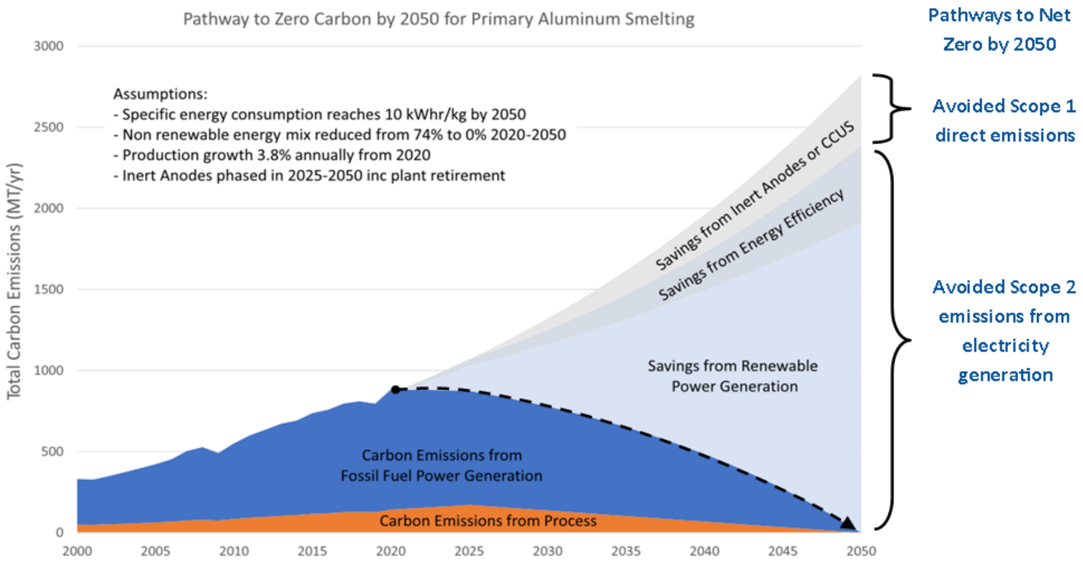

Figure 2. Actual (2000-2020) and modelled CO_2 emissions (2020-2050) from primary aluminium smelting, with a potential pathway to net-zero carbon by 2050. Adapted from [10].

Greenhouse gas (GHG) reduction pathways for aluminium production have been defined by the IAI [7]. These involve complete decarbonisation of electricity generation for the entire aluminium sector – requiring a rapid uptake of clean energy generation, both for new production capacity, which may need to increase by an additional 90 % of today's production [6], and to switch existing production capacity currently using carbon-intensive power.

New power generation from variable renewable energy (VRE) sources is already the cheapest and most environmentally attractive (emission free) method. It was identified recently, for example, that by 2030 up to 90% of energy generation in Australia by wind and solar (PV) could be cheaper than installing any new coal or gas generation capacity [4]. This includes the cost of firming the variable generation, and additional transmission costs, both of which increase with increasing VRE share.

Rapidly increasing the share of variable generation brings practical challenges, such as the traditional need for near-constant energy demand by aluminium smelting. Firming VRE in future will certainly be a key challenge for all energy generators and grid operators [4, 14]. This applies not only to energy networks moving away from existing thermal generation, but also those with largely renewable hydro generation, which will expand in future via VRE generation, and also face challenges due to international and domestic imports and exports of energy, and changes in existing generation patterns due to climate change.

Firming variable generation can be performed by battery storage, pumped and stored hydro, and gas turbine peaking plants and similar technologies. EnPot in comparison works on the premise of demand-side response, utilising existing infrastructure i.e. aluminium smelters. Reducing the usage of major industrial consumers at times of high energy demand on the power grid has a similar practical result as releasing stored energy from a battery or hydro scheme. This has the potential to be the cheapest method to firm up to 40 % of aluminium smelter energy needs (± 20 %) [10, 14] while that power is available, and also provide this amount of power back to the grid as an energy service similar to a grid-scale battery (100 % of firming capacity for a short duration) or pumped hydro (a lower capacity for a longer duration) and in fact a smelter enabled with EnPot technology can return this power back to the grid for an indefinite time. This demand-response mechanism in the electricity market is of high value as smelters are commonly the largest single electricity consumers in their markets. Utilising existing smelter assets results in this being a very low-cost firming option, as shown in comparison in Figure 3.

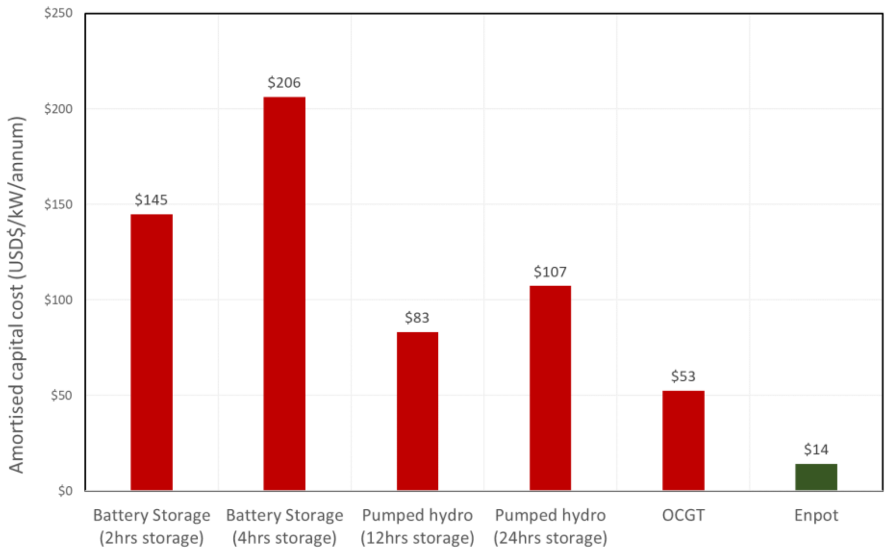

Figure 3. Cost comparison of VRE firming technologies – battery storage, pumped hydro and EnPot.

4. Emissions Reductions by Utilising VRE

While smelter modulation and firming of VRE can have a wider benefit to the whole energy market by enabling further penetration and use of VRE in other industries or locations, the direct reduction in smelter specific emissions can be calculated by replacing a certain amount of thermal power generation with low-emission renewable energy.

Table 1 shows the result of replacing energy generation at a coal-powered smelter with 1) 25% VRE energy, representing 20 % downwards and 5 % upwards modulation on demand, and 2) total replacement with VRE involving this modulation plus other methods of firming.

Table 1. Emissions when replacing 25 % or 100 % of coal power generation with VRE.

	Baseline	**Case 1 (25 %)**	**Case 2 (100 %)**
Scope 2 Emissions, t CO_2e p.a.	3 942 000	3 011 250	219 000
Scope 2 Emission Savings vs. Baseline, t CO_2e p.a.	-	930 750	3 723 000
Total (Scope 1 and 2) Specific Emissions, t CO_2e/t Al	14.8	11.8	2.7

These calculations use assumed figures for an average-sized smelter of 500 MW power consumption, at global average of 14.273 AC kWhr/kg Al [8] and using emissions factors of 0.9 t CO_2e/MWh for coal power generation and 0.05 t CO_2e/MWh for renewables [9], and scope 1 specific emissions of 2.0 t CO_2e/t Al also at the global average [5]. These reductions in scope 2 emissions are equivalent to a total reduction in smelter emissions by 20 % in Case 1, and 80 % in Case 2 respectively.

5. Analysis of Modulation Value to Power Market

The value of a nominal 500 MW (275 000 tonnes p.a.) smelter acting as demand-side response in a specific (anonymised) energy market was analysed, using a local expert in pricing and modelling of that market. The resulting value is specific to the modulation options specified below, and the price shape and projections for this market. The market investigated here is largely supplied by fossil fuel generation, with coal generation contributing nearly 75 % of total supply. This market is changing however, with a rapid increase in solar and wind VRE generation every year, which was included in the market projections. The capital cost of retrofitting this smelter with EnPot technology is around € 50 M.

One key feature of this market is the risk of weather-related emergencies in summer, such as the failure of generators and interconnects. This results in unpredictable shortages and extreme power prices exceeding € 5 000 per MWh, typically lasting from 0.5 to 6 hrs duration. These periods are an ideal case for full-smelter shutdowns, the duration and frequency of which can be extended by the insulation capacity of EnPot technology. At many times it is also beneficial for the smelter to modulate 20 % downwards, reducing production, and either sell their unused power back to the market, or be paid by the market or generators for not taking the power.

Additionally, the market has a large number of very-low priced periods, due to ‘must run’ generation, where a smelter can utilise cheap, free, or even negatively-priced power. This is an ideal time for a smelter to modulate upwards, increasing power consumption and metal production at low cost, to make up for times when it modulates downwards and reduces production.

Future demand, generation, and investment forecasts were used to predict spot market prices for the next 20 years, resulting in price-duration curves. These curves are used to determine when the smelter should ideally modulate upwards (take more power), modulate downwards (reduce power consumption) or fully shut down production within allowable limits.

5.1 Modulation Options Enabled by EnPot

The following assumptions were made regarding modulation capabilities for a generic smelter, to analyse the value of EnPot to the market:

a) Full shutdown of the plant (-100 %) for a maximum of 4 hours, up to once per week;
b) -20 % downwards modulation, for any duration, without lead time; and
c) +5 % upwards modulation, for any duration, without lead time.

All modulation options are smelter specific, given the thermal design and robustness of actual pot technologies, and in particular upwards modulation capabilities can be limited by installed bus bar networks, electrical transformer, and gas treatment centre capacities. For this reason, upwards modulation in the generic case is set at +5 %, whereas EnPot technology is physically capable of enabling much larger increases [1].

A modulation window as wide as ±30 % is possible, but not considered here due to the lead time that is needed to implement operational changes such as cell cover thickness. Note that modulation within the ±20 % window is available on-demand and needs no ‘recharge’ period, as thermal balance is maintained throughout. Full shutdown however causes exhaustive thermal losses in the smelting cells, and a thermal recharge and stabilisation period will be required subsequently before another full shutdown can be made, hence the chosen limit of once per week.

5.2 Arbitrage Price

The 'arbitrage price' (in €/MWh) is the power price at which the smelter's profit from aluminium production is the same as the value of the power used i.e. at this price the smelter would receive equal value from making metal, or releasing the power back to the grid (with suitable commercial arrangements in place). This price is affected by the cost of production, and the sale price of metal, such that a high arbitrage price is a proxy for very profitable production of metal and vice versa.

A 'dead band' in the modulation schedule is created so the plant will operate at base load for a significant fraction of time, ideally approaching 50 %. This means that plant production rates will not rapidly change unnecessarily, as the power prices closest to the arbitrage price will not result in much greater income, and rapid repeated changes could reduce plant efficiency. In practice upwards and downwards trigger prices would be carefully calibrated for a specific smelter and energy market against varying sale prices of metal.

5.3 Modulation Value Results

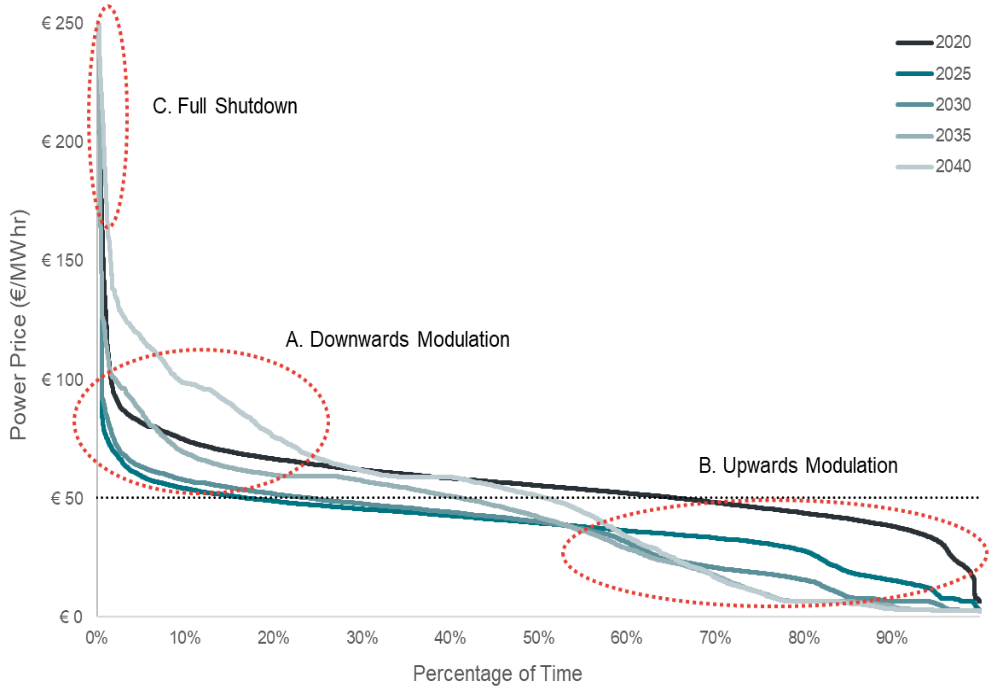

Figure 4. Forecast price-duration curves (2020 to 2040 scenarios) showing different regions of modulation.

The primary results of energy market modelling are the price-duration forecast curves shown in Figure 4, where 5 of the years of energy market price predictions are shown. The price ranges of interest for downwards (A) modulation periods are examined in detail in Figure 5.

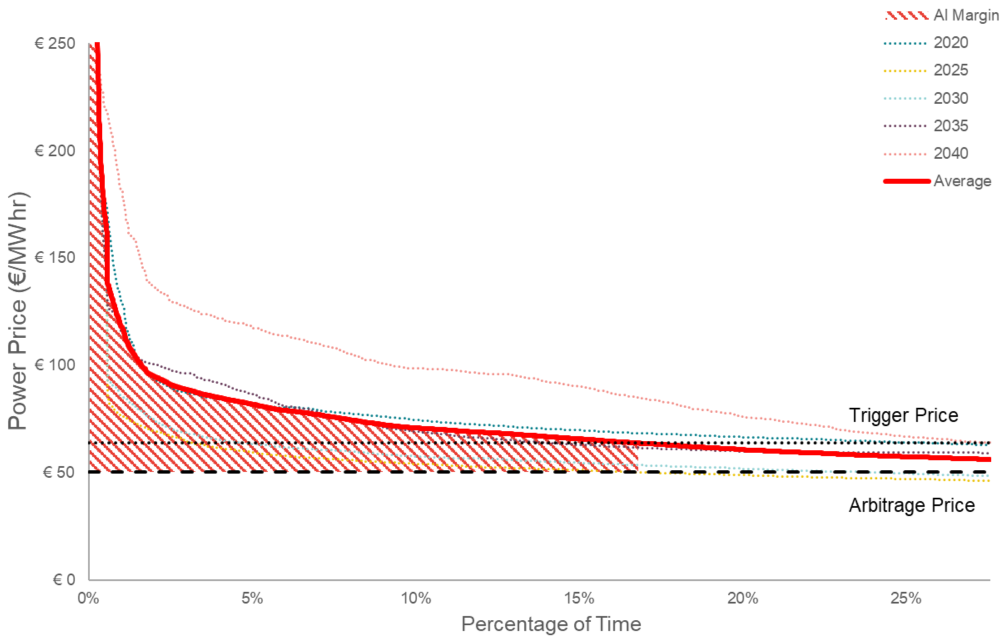

Figure 5. Downwards modulation region (A) for energy market average forecast.

Figure 5 shows the high price events from € 0-250/MWh, where downwards modulation is assumed to trigger at a price of € 63/MWh, which is an estimated arbitrage price of € 50/MWh, plus a dead band of € 13/MWh. When the spot electricity price is above € 63/MWh the smelter would reduce output by 100 MW, and potentially sell this energy on the spot market, or be compensated appropriately by the grid operator or a generator for not consuming this amount of power. In the average forecast, the smelter modulates downwards for 17 % of the year, and the value of the modulation is the electricity price minus the arbitrage price, multiplied by 100 MW released, which in this case is € 11M p.a, represented by the shaded area on the curve.

Conversely when the power price is below € 37/MWh the smelter would increase production and power consumption to make more aluminium at low cost. In the average forecast, the smelter would modulate upwards for 40 % of the time, at an additional 25 MW, and create additional value of € 4 M p.a. This amount would scale by the capability of the plant to modulate upwards by more than 5 % if possible.

Complete shutdown of the plant is assumed when the power price exceeds about € 300/MWh. This value is added for 400 MW beyond the 100 MW already counted in downwards modulation, and limited in frequency by plant operational considerations. In the average price forecast, this is worth € 19 M p.a. The total value of full shutdowns may not be completely captured in cases where shutdowns are longer than the maximum allowable 4 hours, or occur too frequently without sufficient recovery time.

Table 2 aggregates the total income of modulation and shutdown capabilities in this market, being a total of € 34 million p.a. On this basis the payback period of an EnPot installation is estimated to be one to two years.

A sensitivity analysis showed that the total income varied between € 34 M p.a. and € 45 M p.a as the arbitrage price varied between € 35/MWh and € 110/MWh. When the arbitrage price is high (making metal is more profitable) there is more value in modulating upwards, and when the arbitrage price is low (selling power is more profitable) there is more value in modulating downwards.

Table 2. Modulation value results for energy market average prediction.

Arbitrage Price = € 50/MW	**Modulation Assumption**	**% of year in operation**	**MW Impacted**	**Income p.a. M€**
Downwards modulation	-20 %	17 %	100	11
Upwards modulation	+5 %	40 %	25	4
Complete shutdown	-100 %	0.2 %	400	19
Total		**57 %**		**34**

6. Changing Market Dynamics and Energy Crises

Global energy markets are facing pressure from numerous corners and although each market is unique, common themes are clear. Booming demand coupled with tightness of supply has led to rapidly escalating power prices across the board. According to the International Energy Agency we are facing our first truly global energy crisis in history [15]. To date, electricity prices in Europe have been the worst hit but on the other side of the world, similarities can be found in the Australian energy landscape. In June 2022, the Australian Energy Market Operator suspended the spot electricity market in all regions to avoid blackouts. Ensuring a continuous supply of electricity to the nations' homes and businesses was cited as rationale [16].

In the lead-up to this unprecedented suspension, Australia saw significant unplanned outages at coal-fired power plants and squeezed gas supply amid increased demand resulting from an early winter cold snap coinciding with low wind and solar output. Those events added renewed urgency for calls to overhaul the structure of Australia's energy market - to introduce a mechanism to reward power producers for their capacity to fill gaps in generation, not just for the power they produce. As the proportion of VRE in the national grid increases, this capacity is likely to become more critical. Similar structural reform is also being called for to support the European Aluminium Industry which has lost ~30 % of its primary production capacity since 2008, despite the steadily growing demand for aluminium in Europe and around the world [17]. In all regions demand side response is growing in popularity as a low-cost, rapidly deployable way to firm VRE and limit exposure to volatile global commodity markets.

The forecasts for 2020-2040 prices used in the modelling above encompassed a wide range of inputs including demand, generation, and investment signals, and the total value of modulation was analysed using the average forecast price for this period. Due to ongoing rapid changes such as the Australian and European energy crises, it was decided to compare this against actual power prices for calendar year 2020, and the 12 months preceding July 2022. The changing shapes of the price-duration curves for these periods are shown in Figure 6.

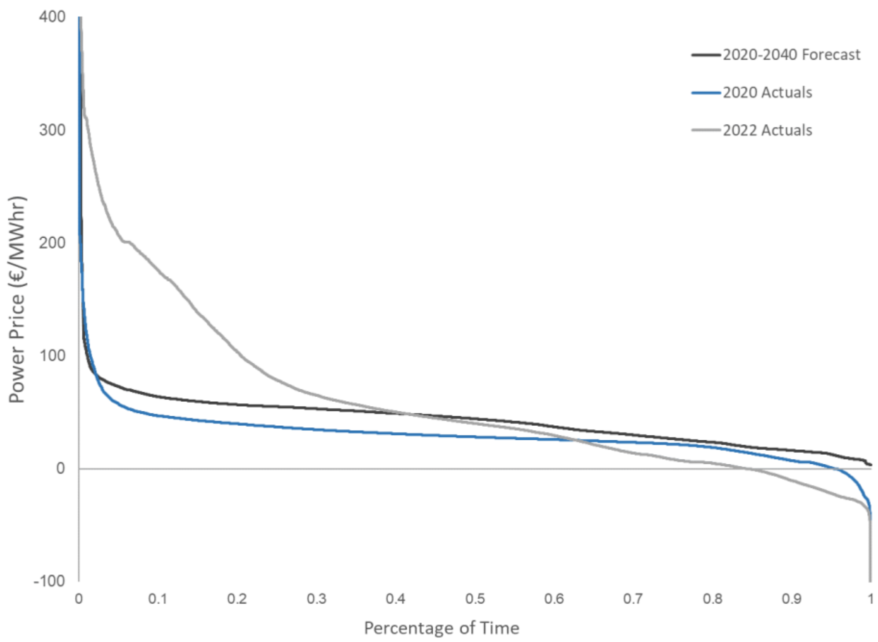

Figure 6. Changing energy market prices from initial 2020-2040 forecast against 2020 and 2022 actual prices.

The actual price curve in 2020 is not largely different from the average prediction, however, it can be seen in the value results presented in Table 3 that there is significantly higher value for complete shutdowns in 2020 than forecast, while occurring a lesser amount of time i.e. the emergency situations requiring full shutdown have much higher power prices than forecast and a smelter would be very well rewarded by returning power to the grid at this time, with the total yearly value increasing by € 10 M to € 44 M p.a.

Table 3. Modulation income and usage results for changing energy market shapes.

	Market Forecast 2020-2040, M€ p.a.		**Actual Prices 2020, M€ p.a.**		**Actual Prices 2022, M€ p.a.**	
Downwards Modulation	11	17 %	9	4 %	41	31 %
Upwards Modulation	4	40%	7	75 %	7	46 %
Complete Shutdown	19	0.2%	27	0.1 %	19	0.6 %
Total Income € M, % usage	**34**	**57 %**	**44**	**78 %**	**67**	**78 %**

The analysis of 2022 power prices shows an even greater increase to a yearly value of € 67 M p.a, giving a capital payback period of less than one year. This is due to the huge increase in downwards modulation value, seen as much longer periods of high prices for around 30 % of the year in Figure 6. These long periods of high prices were not seen in the forecasts in Figure 4 until 2040, however the rapidly changing energy market and power crisis has brought about this situation much sooner. Such a large change in power prices from 2020 to 2022 underscores the ongoing crises caused by imbalances and challenges in energy generation, changing demand, VRE firming, energy transmission, and international and domestic energy import/export, and even war.

7. Barriers for Adoption

The technical development of the EnPot system was completed via trial at several smelters by the Light Metals Research Centre at the University of Auckland [1, 11, 12]. It is currently operational on a full potline at the TRIMET Essen smelter [2, 13] and a 10-pot section at TRIMET Hamburg. A key barrier for further adoption is general industry acceptance of the performance and robustness of the technology, and EnPot's intention is to prove this via subsequent demonstration trials on other pot technologies, operating in other electricity markets. EnPot is ready for full-potline or smelter implementations once the technology has been accepted by a smelter.

Depending on the electricity market and prevailing conditions, paybacks have been calculated from between 1 and 4 years for an EnPot installation. At the longer end, this can be challenging when some smelters are operating with short power purchase agreements of similar duration. Power purchase agreements also need to be updated to appropriately value modulation by the smelter. Rapidly changing power markets and increasing value for modulation as detailed above may give shorter and more favourable payback periods, however these rapid changes and instability may also discourage investments. It is encouraging however that governments, energy providers, and wider industry are all rapidly pivoting towards net-zero carbon emission goals, and funding is becoming available for investments such as EnPot. Involving multiple partners such as governments, energy grid operators, green funds, as well as smelters may result in complicated and slow-moving negotiations however, which may be less preferable than smelter-funded.

8. Conclusions

Decarbonisation of power systems by increasing VRE generation is by far the most impactful way to reduce Scope 2 CO_2 emissions of aluminium smelters. However, VRE has significant firming requirements be useful for smelters that have traditionally required very stable energy input. EnPot technology is the most cost effective solution to deal with varying power availability, to firm up to 40 % of smelter power needs, and allow smelters to benefit commercially from providing these firming services to their electricity markets.

Modelling was undertaken to examine the value of smelter modulation in a specific energy market, showing value of € 34 M p.a for a 500 MW smelter, based on expert forecasts from 2020-2040. Rapid changes in energy markets, and energy crises in the last two years however have shown that value could have increased to as much as € 67 M p.a already, making payback periods for an EnPot installation much shorter. These energy market challenges are expected to continue into the foreseeable future, or at least until the end of 2024, according to the World Bank [18]. Combined with increased governmental, corporate and consumer desires to decarbonise, smelter power modulation is a very attractive proposition.

Acknowledgements

The authors wish to thank the teams who performed the energy and financial modelling (kept anonymous so as not to identify any particular smelter), and also previous work in this area by Geoff Matthews and Mark Dorreen.

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