TRANSPORTATION MODEL FOR CARBON-CONSTRAINED ELECTRICITY PLANNING: AN APPLICATION TO THE ALUMINIUM INDUSTRY

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Abstract Aluminium production is one of the most highly energy-intensive processes and consequently one of the largest sources of greenhouse gas (GHG) emissions. A large portion of these emissions are indirect emissions, owing to consumption of electricity. Various Process Integration techniques have been developed for energy consumption and/or GHG footprint targeting and reduction. In this paper, a transportation model for carbon-constrained electricity planning is proposed. The model is applied to specific aluminium products, slugs and evaporators, and implemented within a General Algebraic Modelling System (GAMS) environment. The proposed model calculates optimal allocation of electricity sources to reach the CO2 emission benchmark set by the European Union. Results show that meeting the CO2 emission benchmark will increase costs by 26 % when current electricity prices are considered.

Keywords:
carbon emission pinch analysis, GHG emissions, transportation model, aluminium industry, benchmark.

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1 Introduction

Primary aluminium is produced by the electrolytic reduction process, where aluminium is separated from the alumina (Al_2O_3) within a cell. The current is passed from the anode to the cathode during this process (Kvande, 2014). According to data from the International Aluminium Institute (World Aluminium, 2019), on average, 14,210 kWh of electricity was used to produce 1 t of primary aluminium in 2018. This makes aluminium production one of the most highly energy-intensive processes and consequently one of the largest producers of greenhouse gas (GHG) emissions. A large portion of these emissions are indirect emissions, which is the result of electricity consumption, while direct GHG emissions are also considerable. Direct emissions could be reduced by a using higher share of secondary aluminium, by implementation of carbon capture technology, by using inert anodes and other strategies, while indirect GHG emissions could be reduced by changing energy sources toward renewable and other low-carbon sources of electricity (Gomilšek *et al.*, 2019).

Various Process Integration techniques have been developed for reduction of the GHG footprint. One promising technique is Carbon Emission Pinch Analysis (CEPA), which was first introduced by Tan and Foo (Tan & Foo, 2007). CEPA is a Pinch Analysis (PA) procedure for identifying the minimum number of low- or zero-carbon energy sources needed to achieve the specified emission limit/target (Tan & Foo, 2007). CEPA methodology has been further extended and applied to the analysis of energy sectors in the Philippines (Foo *et al.*, 2008), Ireland (Crilly & Zhelev, 2008), New Zealand (Atkins *et al.*, 2010), the USA (Walmsley *et al.*, 2015), China (Jia *et al.*, 2016), Nigeria (Salman *et al.*, 2019) and other countries. It has also been applied to systems at different scales, extended through the use of alternative metrics and footprints, and has been integrated with Input-Output Analysis to include economic aspects (Tan *et al.*, 2017).

Various approaches exist for the synthesis and retrofit of Process Integration (PI) systems, such as heat and mass exchanger networks (HENs and MENs), and carbon management networks. Approaches could be based on heuristics, on thermodynamic insights (PA), on numerical optimization (Mathematical Programming – MP) and on hybrid or combined approaches (Čuček *et al.*, 2019). The most widely used approach to carbon-constrained planning is the PA approach

(CEPA). Often it is combined with MP as part of a hybrid approach (Tan & Foo, 2007). A mathematical formulation has also been developed in the form of what is called a crisp model, minimizing the total amount of the zero-emission energy resource (Tan & Foo, 2007).

In this study, a transportation model for carbon-constrained electricity planning is proposed, which enables the use of various optimization criteria to guide the search. The transportation model for carbon-constrained electricity planning has been applied to specific aluminium products, slugs and evaporators, and implemented within a General Algebraic Modelling System (GAMS) environment.

2 Model development

Several methods based on MP exist for solving PI problems. The transportation model (Cerda *et al.*, 1983) was one of the first problem formulations, while various MP formulations followed, such as the transhipment and expanded transhipment models (Papoulias & Grossmann, 1983), the stage-wise problem (Yee & Grossmann, 1990) and several others (Čuček *et al.*, 2019). Since both mass and energy are extensive properties, the transportation model is a suitable method for solving carbon-constrained electricity planning problems.

In the model, two main sets are defined:

- Set *i* represents various energy sources, e.g. fossil, nuclear and renewable;
- Set *j* represents various products. In this study, two specific products from aluminium production are considered. These are slugs and evaporators, which are both produced by the company.

The transportation model comprises supply and demand nodes. The supply nodes represent the supply or availability of various energy sources (a_{i}). The demand nodes represent the demand or consumption of electricity (b_{j}). The amount of electricity from supply to demand (x_{ij}) is a positive variable. Eq. (1) specifies that availability of energy sources must be greater than or equal to the sum of electricity consumed for all *j* products considered for every energy source *i*.

$$\sum_{\mathrm{j}} x_{\mathrm{ij}} \leq a_{\mathrm{i}} \quad \forall i \tag{1}$$

The sum of electricity consumption of energy sources from supply to demand must be equal to the electricity consumed by each product *j*, as shown in Eq. (2):

$$\sum_{\mathrm{i}} x_{\mathrm{ij}} = b_{\mathrm{j}} \quad \forall j \tag{2}$$

CO_2 emissions from electricity use for producing the considered amounts of products (E_{j}) are calculated with Eq. (3), where x_{ij} is multiplied by the emission factors of energy sources *i* (F_{i}) for each product *j*:

$$\sum_{\mathrm{i}} x_{\mathrm{ij}} \times F_{\mathrm{i}} = E_{\mathrm{j}} \quad \forall j \tag{3}$$

The fraction of electricity source *i* used for producing each product *j* (w_{ij}) is calculated by Eq. (4):

$$w_{\mathrm{ij}} = \frac{x_{\mathrm{ij}}}{b_{\mathrm{j}}} \quad \forall i, j \tag{4}$$

The objective considered is minimization of costs (OBJ), which is calculated by Eq. (5) by multiplying x_{ij} with the cost of energy source *i* (P_{i}):

$$\mathrm{OBJ} = x_{\mathrm{ij}} \times P_{\mathrm{i}} \quad \forall i, j \tag{5}$$

3 Results and discussion

The carbon-constrained electricity planning problem has been solved for two aluminium products, slugs and evaporators, applying the proposed transportation model and a GAMS modelling environment. Three different scenarios were performed:

- Scenario 1 (Current): CO_2 emissions for every product are fixed to actual values, since they represent the current case, with defined fractions of energy sources.

- Scenario 2: Fractions of energy sources are relaxed, and CO_2 emissions are fixed to new values to meet the requirements of the benchmark set by the European Union (European Commission, 2019), which should be achieved for each product separately.
- Scenario 3: Similar to that in Scenario 2; however, the overall emission benchmark should be achieved.

The carbon footprint composite curves for the second and third scenarios are shown in Figure 1 and Figure 2, where the current case (current electricity mix to satisfy consumption) crosses the benchmark line in both scenarios. Consequently, electricity sources with smaller emission factors (nuclear and/or renewable) should replace fossil resources in the electricity mix. Moreover, in both scenarios 2 and 3, the benchmark has been achieved. Only nuclear energy has been selected, owing to both the smaller emission factor and the price, compared to those for renewable sources. It should be noted that, for reasons of confidentiality, the values of emissions are normalized, where the value of 1 represents the current emissions.

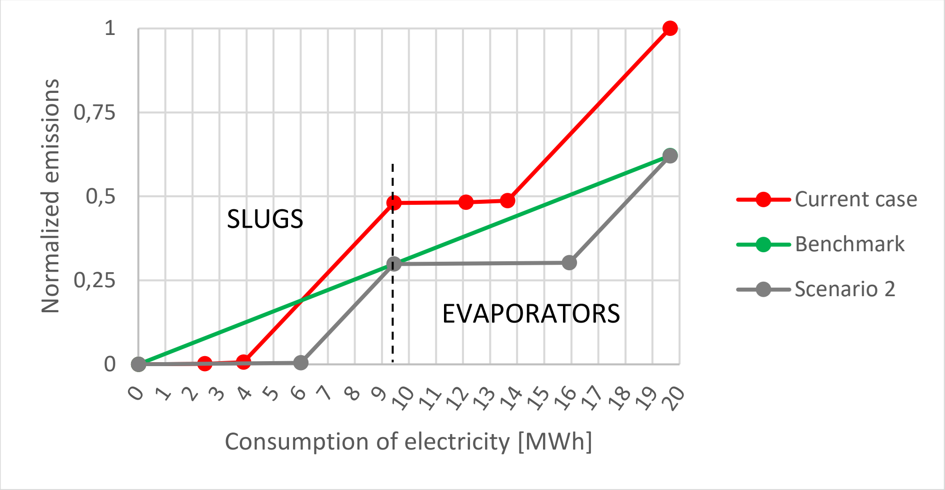

Figure 1: CO_2 footprint composite curve for Scenario 2.

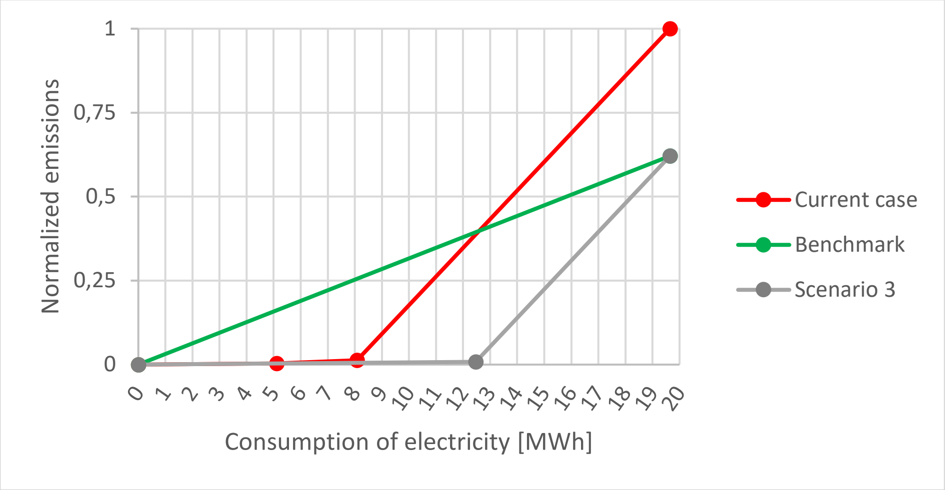

Figure 2: CO_2 footprint composite curve for Scenario 3.

The total cost of the process for all three scenarios considered is presented in Table 1, where it can be seen that costs for both scenarios 2 and 3 are increased by 26 %, compared to the base case. These higher costs are due to the increased share of nuclear energy, which is more expensive than fossil energy. Similarly, as in Figures. 1 and 2, the values of costs are normalized.

Table 1: Total cost of various scenarios.

	Current	**Scenario 2**	**Scenario 3**
z	1	1.26	1.26

4 Conclusions

This paper presents a transportation model for carbon-constrained electricity use for producing aluminium slugs and evaporators. The proposed model calculates optimal allocation of electricity sources to reach the CO_2 emission benchmark. It was shown that the cost of electricity supply would increase by 26 % over current prices of electricity if the company wants to meet the requirements of the CO_2 emissions benchmark.

In the future, the model will be expanded with predictions of future prices of electricity sources, a more detailed electricity consumption mix, more detailed electricity pricing, and to include consumption of other energy sources for heating and cooling.

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References

Atkins, M. J., Morrison, A. S., Walmsley, M. R. W. (2010). Carbon Emissions Pinch Analysis (CEPA) For Emission Reduction in the New Zealand Electricity Sector. *Applied Energy, 87*, 982-987. doi: 10.1016/j.apenergy.2009.09.002.

Cerdá, J., Westerberg, A. W., Mason, D., Linnhoff, B., (1983). Minimum Utility Usage in Heat Exchanger Network Synthesis. *Chemical Engineering Science, 38 (3),* 373-387. doi: 10.1016/0009-2509(83)80156-0.

Crilly, D., Zhelev, T. (2008). Emissions targeting and planning: An application of CO2 emissions pinch analysis (CEPA) to the Irish electricity generation sector. *Energy, 33*, 1498-1507. doi: 10.1016/j.energy.2008.05.015.

Čuček, L., Boldyryev, S., Klemeš, J. J., Kravanja, Z., Krajačić, G., Sabev Varbanov, P., Duić, N. (2019). Approaches for retrofitting heat exchanger networks within processes and Total Sites. *Journal of Cleaner Production, 211,* 884-894. doi: 10.1016/j.jclepro.2018.11.129.

European Commission. Commission delegated regulation (EU) 2019/331 of 19 December 2018 determining transitional Union-wide rules for harmonised free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council. Brussels: Official Journal of the European Union, 2019.

Foo, D. C. Y., Tan, R. R., Ng, D. K. S. (2008). Carbon and footprint-constrained energy planning using cascade analysis technique. *Energy, 33 (10)*, 1480-1488. doi: 10.1016/j.energy.2008.03.003.

Gomilšek, R., Čuček, L., Homšak, M., Kravanja, Z. (2019). Towards GHG Emissions Neutrality of Aluminium Slug Production: An Industrial Study, accepted manuscript for 22nd Conference Process Integration, Modelling and Optimization for Energy Saving and Pollution Reduction – PRES'2019, 20 – 23 October 2019, Crete, Greece.

International Aluminium Institute. Current IAI statistics, Primary aluminium smelting energy intensity. http://www.world-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/ (accessed: 7.9.2019).

Jia, X., Li, Z., Wang, F., Foo, D. C. Y., Tan, R. R. (2016). Multi-dimensional pinch analysis for sustainable power generation sector planning in China. *Journal of Cleaner Production, 112 (4)*, 2756-2771. doi: 10.1016/j.jclepro.2015.10.102.

Kvande, H. (2014). The Aluminium Smelting Process. *Journal of Occupational and Environmental Medicine, 56, S2-S4*. doi: 10.1097/JOM.0000000000000154.

Lee, S. C., Ng, D. K. S., Foo, D. C. Y., Tan, R. R. (2009). Extended pinch targeting techniques for carbon-constrained energy sector planning. *Applied Energy, 86 (1)*, 60-67. doi: 10.1016/j.apenergy.2008.04.002.

Papoulias, S. A., Grossmann, I. E., (1983). A structural optimization approach in process synthesis-II: Heat recovery networks. *Computers & Chemical Engineering, 7 (6),* 707-721. doi: 10.1016/0098-1354(83)85023-6.

Salman, B., Saifuddin, N. M., Foo, D. C. Y. (2019). Carbon emissions pinch analysis (CEPA) for energy sector planning in Nigeria. *Clean Technologies and Environmental Policy, 21 (1)*, 93-108. doi: 10.1007/s10098-018-1620-5.

Tan, R. R., Foo, D. C. Y. (2007). Pinch analysis approach to carbon-constrained energy sector planning. *Energy*, *32*, 1422-1429. doi: 10.1016/j.energy.2006.09.018.

Tan, R. R., Aviso, K. B., Foo, D. C. Y. (2017). Economy-Wide Carbon Emissions Pinch Analysis. *Chemical Engineering Transactions, 61*, 913-918. doi: 10.3303/CET1761150.

Walmsley, M. R. W., Walmsley, T. G., Atkins, M. J. (2015). Achieving 33% renewable electricity generation by 2020 in California. *Energy, 92*, 260-269. doi: 10.1016/j.energy.2015.05.087.

Yee, T. F., Grossmann, I. E. (1990). Simultaneous optimization models for heat integration-II. Heat exchanger network synthesis. *Computers & Chemical Engineering, 14 (10),* 1165-1184. doi: 10.1016/0098-1354(90)85010-8.