

# Open and Common Approaches for Evaluating Marginal Emission Factors: A Case Study of the Alberta Electric Grid

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### Abstract

Future energy scenarios for the electricity sector must include reliable emission factors at the very time the energy is consumed to account for changes in load and generation. This report compares the hourly marginal emission factors (MEFs) estimated for the province of Alberta for the year 2018 using two different approaches: a multiple linear regression model (MLR) and the Canadian Energy Regulator (CER) Energy Futures model. The models are evaluated by comparing their results for the fraction of the time that different generator types are marginal on an annual basis to data provided by the Alberta Electric System Operator (AESO). Results from the CER model are much closer to those of the AESO than those of the simpler MLR model, which significantly underestimates the fraction of time that coal generators are marginal, and significantly overestimates the fraction of time that gas and hydroelectric generators are marginal. In line with this, the MEF predictions from the two models are quite different: the annual average MEF predicted by the MLR model is 693 kg of  $CO_2/MWh$  whereas the CER model estimates this value at 842 kg of CO<sub>2</sub>/MWh. Average MEFs are computed for each model by month and hour of the day to examine systematic patterns that could be used for instance to schedule loads such as electric vehicle charging. Again, the two models give significantly different results: there is much less variability across months and hours with the MLR model as the standard deviation is of only 4 kg of CO<sub>2</sub>/MWh compared to 126 kg of CO<sub>2</sub>/MWh for the CER model.

i

### Résumé

Les scénarios énergétiques futurs pour le secteur de l'électricité doivent inclure des facteurs d'émission fiables au moment même où l'énergie est consommée pour tenir compte des changements dans la demande et la production. Ce rapport compare les facteurs d'émission marginaux (FEM) horaires estimés pour la province de l'Alberta pour l'année 2018 à l'aide de deux approches différentes : un modèle de régression linéaire multiple (MLR) et le modèle Energy Futures de la Régie de l'énergie du Canada (REC). Les modèles sont évalués en comparant leurs résultats pour la fraction du temps où les différents types de générateurs sont marginaux sur une base annuelle aux données fournies par l'Alberta Electric System Operator (AESO). Les résultats du modèle REC sont beaucoup plus proches de ceux de l'AESO que ceux du modèle plus simple MLR, qui sous-estime considérablement la fraction de temps pendant laquelle les générateurs au charbon sont marginaux, et surestime considérablement la fraction de temps pendant laquelle les générateurs au gaz et hydroélectriques sont marginaux. Dans le même ordre d'idées, les prévisions de FEM des deux modèles sont très différentes : le FEM moyen sur une base annuelle prévu par le modèle MLR est de 693 kg de CO<sub>2</sub>/MWh alors que le modèle REC estime cette valeur à 842 kg de  $CO_2/MWh$ . Les FEMs moyens sont calculés pour chaque modèle par mois et par heure de la journée afin d'examiner les tendances systématiques qui pourraient être utilisées, par exemple, pour programmer des charges telles que la recharge des véhicules électriques. Encore une fois, les deux modèles donnent des résultats très différents : il y a beaucoup moins de variabilité parmi les données par mois et par heure de la journée avec le modèle MLR, puisque l'écart type n'est que de 4 kg de  $CO_2/MWh$ , contre 126 kg de  $CO_2/MWh$  pour le modèle REC.

ii

## **Table of Contents**

1.	Introduction	5
2.	Literature Review	8
3.	Model and Methodology	.12
	3.1. Multiple Linear Regression (MLR) Model	. 12
	3.2. CER Model	. 14
4.	Data Sources	.16
5.	Results and Analysis	.18
6.	Discussion	.22
7.	Future Work	.24
Refe	rences	.25

### **List of Tables**

Table 1: Sources for the inputs of the different models	16
Table 2: Fraction of time different generator types are on the margin	19
Table 3: Fraction of total generation provided by different generator types	19
Table 4: Statistical properties of the distribution of MEFs (kg of CO <sub>2</sub> /MWh) in Figure 2	19
Table 5: Statistical properties of the distribution of AEFs (kg of CO <sub>2</sub> /MWh) in Figure 3.	21

## List of Figures

gure 1: Share of Energy Production by Generation Technology, Alberta, 2014-2019 [2]
gure 2 : Average MEFs by hour and month for the two models (kg of $CO_2/MWh$ ) 20
gure 3 : AEFs by hour and month estimated from AESO data and the CER model (kg of
0 <sub>2</sub> /MWh)

#### 1. Introduction

Developing sound policies for energy planning requires a clear science-based demonstration of the environmental impact that may ensue. Electricity represents 10% of Canada's greenhouse gas (GHG) emissions even if more than 80% of electricity in Canada comes from non-GHG emitting sources [1]. Whereas baseload production is relatively clean overall, the imbedded carbon intensity still varies depending on location, time of day and day of year. Thus, future energy scenarios for the electricity sector must include reliable emission factors at the very time the energy is consumed to account for changes in load (e.g. from electric vehicle (EV) charging) and generation. Most of the models that can carry these studies are either proprietary or incomplete and the data to run the simulation or train the models are often unavailable to the research community.

Emission factors for electricity generation in Canadian provinces are generally provided as annual averages. Average emission factors is one type of metric that can be used for strategic assessments such as climate change policy comparisons. However, when for example assessing the impact of specific technologies, alternative metrics may be considered to quantify GHG emissions. One of these metrics is marginal emission factors (MEFs) that provide the emissions impact resulting from an incremental unit of electricity demand, such as an electric vehicle. In the last few years, different approaches have been developed to quantify hourly MEFs. Unfortunately, there have been few attempts at comparing these different approaches particularly in the Canadian context where the electricity market is segmented across provincial utilities. This project conducts a review of models to calculate hourly MEFs and a comparison of two approaches using a specific province as a case study. This report focuses on the Alberta electric grid as a case study. Alberta's electric system represents an interesting case study for a variety of reasons. First, data is available on the hourly electric generation of each generator from the Alberta Electric System Operator (AESO). Second, Alberta has an increasingly diverse grid containing renewables, coal, and natural gas generation which is flexible to various degrees (Figure 1). This creates the possibility that the MEFs and average emission factors (AEFs) could be significantly different. Finally, while Alberta does have interties with neighbouring regions, these represent a fairly small share of electricity generation in the province. Therefore, the comparisons across estimation techniques should not be especially biased by how detailed they are with respect to coverage of neighbouring regions.



Figure 1: Share of Energy Production by Generation Technology, Alberta, 2014-2019 [2]

The objectives of this study are to:

• Build a "fair" approach (including common inputs/outputs and comparison metrics) to compare the different MEF calculation models

- Identify data required to estimate reliable hourly MEFs
- Investigate methods to fill data gaps and model gaps
- Compare approaches (specific to the requirements e.g. small vs big incremental load) for calculating hourly MEFs

At first, a literature review of MEF calculation methods was performed to identify the approaches to pursue. This was followed by defining the modelling framework required for selected approaches, e.g. inputs and comparison metrics. Once the framework was defined, the data required for selected modelling approaches was collected. The hourly MEFs were then modelled, evaluated and compared using different approaches for the Alberta electric grid.

#### 2. Literature Review

Electricity greenhouse gas emission factors indicate how much carbon would be emitted or saved by changing electricity usage in terms of kg of carbon dioxide emissions per MWh of power usage (kg of CO<sub>2</sub>/MWh). Emissions taken into account are associated with power generators and transmission/distribution losses. Two types of greenhouse gas emission factors are commonly used for such assessment:

- Average Emission Factor (AEF) which is defined as the ratio of CO<sub>2</sub> emitted to electricity generated. It represents the average kg of CO<sub>2</sub>/MWh of electricity consumed at the point of final consumption.
- Marginal Emission Factor (MEF) which is defined as the incremental change in carbon dioxide emissions as a result of an increase in demand.

A variety of public and commercial assessment tools have been used to calculate emissions from electricity usage. They range in complexity from simple emission factors to multifaceted grid models with market-based dispatch of generation assets. Some articles provide a comprehensive comparison of various methods to give a general overview of the techniques available and the impact of model selection. Thirty-two methods and models are identified and reviewed in [3]. The methods and models are then classified into two distinct categories: i) empirical data and relationship models, including eGRID and AVERT which use historical data and are not necessarily adapted to predict future emissions, and ii) power system optimization models to address economic dispatch, unit commitment and capacity planning for long-term changes.

**Relationship models:** Development of empirical data and relationship models has been showcased and discussed in numerous publications. In [4], the output of each

generator, system load and picture of the future generation mix are used to calculate hourly and monthly MEFs using a linear regression model. Regression techniques are used in [5] to compute MEFs and to determine the marginal generator type using changes in emission and generation. A statistical method is introduced in [6] to determine capacity factors for each generator type depending on the load, decide on the dispatch and compute the emissions, having a large penetration of EVs in mind. In [7], a relationship model is developed between emissions and consumption using a least square technique. Also, regression coefficients are calculated for individual regions in a state in order to compute MEFs by location in the same market zone. The AVERT tool [8] implements a statistical approach using emission, generation and load data to calculate MEFs. The methodology is based on Monte Carlo analysis and includes computation of the frequency of operations for fossil-fuel generators. The focus of the analysis in [9] is the greater Toronto and Hamilton area in Ontario where hourly MEFs are calculated using multiple linear regression models. Also, GHG emissions associated with EV charging are estimated at two penetration rates (5% and 30%) using five charging scenarios: home, work and shopping, night, downtown versus suburbs and an optimal low-emission charging scenario, matching charging time with the lowest available MEFs. A machine learning approach is used in [10] which employs support vector machine regression to estimate marginal emissions with load and wind data among inputs. Marginal emissions are also calculated by linking local marginal prices to the generation type on the margin and associating an emission factor to each generator type [11][12].

**Power system optimization models:** the use of power system optimization models is attested in [13] with the simulation of the entire electricity system using PROMIX, with different demand possibilities to evaluate the impact of demand changes. PLEXOS market model software is used in [14] to model the grid and to do a case study on the impacts of EV charging (with charging scenarios). The TIMES modelling

environment is employed in [15] to report the account of structural and operational effects in electricity systems on the calculation of MEFs in the long-run. The above works are followed by a unit commitment model for New York State with scenarios of change in electricity grid up to 2025 [16] and a model of the California electricity grid capable of differentiating hourly and seasonal GHG emissions by generation source incorporating the potential use of different types of plug-in hybrid electric vehicles [17]. The Electricity Dispatch model for Greenhouse gas Emissions in California (EDGE-CA) is introduced in [18] where it simulates near-term electricity supply on an hourly basis in order to estimate emissions from marginal generation for vehicle and fuel demands. As a spreadsheet-based accounting tool, it determines the capacity and allocates generation among available power plants to meet demand in three regions of California, including imported power from out of state. Simulation of the operation of national energy systems in Denmark is showcased in [19] on an hourly basis using a user-friendly interface and including the electricity, heating, cooling, industry, and transport sectors. Finally, Integrated Planning Model (IPM) of the electric power sector is presented in [20] which is designed to help government and industry analyze a wide range of issues such as economic activities in key components of energy markets. The applications of IPM include capacity planning, environmental policy analysis and compliance planning, wholesale price forecasting and asset valuation. It also captures the linkages in electricity markets which leads to integrated analysis of the impacts of alternative regulatory policies on the power sector.

**Electric vehicles:** As the usage of EVs increases, calculation of emissions related to these vehicles – both conception and operation – becomes a topic of interest for case studies. The emissions of EVs across their whole life cycle are addressed in [21] while the computation of the EV footprint with marginal emission factors for the USA electricity system is discussed in [22]. The computation and comparison take into

account marginal grid mix, ambient temperature, patterns of vehicle miles travelled and driving conditions. The method described in [23] uses short run marginal cost curves and a dispatch merit order strategy to compute the emissions factor and apply it to the EVs. Finally, studies covering the longer-term planning of EV incorporation include [24] where long-term effects of large penetration rate of EVs are modelled using MEFs determined by a dispatch algorithm.

The above literature review briefly shows the vast scope of work already done or in progress regarding the evaluation of GHG emissions. Different models focus on certain elements which are often region-specific such as current energy policies, generation mix and power systems, EV market penetration and so on. It is important to have the right values regarding the emissions as understanding and quantifying the impact of GHG emissions is a key element for electrification studies. To do this, the present study provides a comparison of different models developed and used in Canadian institutes, as the first step in building a consensus for generating this type of information required for decarbonisation and electrification studies within the Canadian context.

### 3. Model and Methodology

Two models were selected for the comparison and are described in the following sub-sections:

- A multiple linear regression model
- The Canadian Energy Regulator (CER) Energy Futures model

These models were run for the year 2018 for the Alberta grid and compared based on their predicted average hourly marginal emission factors for each month of the year and hour of the day. No actual data on hourly marginal and/or average emission factors for the Alberta grid are available making the validation of the models challenging. The AESO does provide, however, the fraction of time different generator types are on the margin on an annual basis as well as the fraction of total generation provided by different generator types. These two metrics were therefore used as the primary means of evaluating the different models when possible, i.e. when the model provided outputs that allowed calculating these metrics.

#### 3.1. Multiple Linear Regression (MLR) Model

The multiple linear regression model of marginal greenhouse gas emission factors is based on the work of [9] at the University of Toronto. In this model, MEFs depend both on the total generation level G and on the change in total generation from one hour to the next ( $\Delta G$ ), as follows:

$$\Delta E = \overbrace{(\beta_1 + \beta_2 G + \beta_3 \Delta G)}^{MEF} \Delta G + \beta_0 \tag{1}$$

where  $\Delta E$  is the change in total GHG emissions from one hour to the next and the expression in parentheses (red font) is the marginal emission factor for a given hour.

(This expression corresponds to MLR2 in the terminology of [9], but with the addition of the constant term  $\beta_0$ .)

In the same vein, this model was extended in [25] to provide the fraction of time ( $\gamma_k$ ) that each generator type is marginal, via the following equations:

$$\Delta G_k = \overbrace{\left(\in_{1,k} + \in_{2,k} G + \in_{3,k} \Delta G\right)}^{\gamma_k} \Delta G + \in_{0,k}$$
(2)

where k corresponds to the generator type (e.g. coal, gas, hydro, wind) and  $\Delta G_k$  is the change in generation levels for generators of type k from one hour to the next.

Prior to fitting this model, the hourly generator output data were filtered to remove generators that could not be marginal for each hour. Only coal, gas and hydro generators were considered as potentially marginal based on AESO annual market statistics data [2]. In addition, generators were excluded from the marginal generation pool for a given hour when their change in generation was of opposite sign to the change in the total generation. After data filtering, the coefficients of the model ( $\beta_0$ ,  $\beta_1$ ,  $\beta_2$ ,  $\beta_3$ ,  $\in_{0,k}$ ,  $\in_{1,k}$ ,  $\in_{2,k}$ ,  $\in_{3,k}$ ) were obtained by fitting the model to hourly AESO data for all of 2018.

[25] evaluated different versions of simple linear regression, multiple linear regression and artificial neural network models using data from Ontario (IESO) and Alberta (AESO), and found that the multiple linear regression model in equation (1) performed well overall in terms of predicting changes in emissions from one hour to the next [25]. However, one limitation of this model is that it is trained on historical data. As such, it remains valid only to the extent that the generation fleet remains sufficiently similar to what it was during the period used for model training.

#### 3.2. CER Model

The Canada Energy Regulator (CER) approach uses components of its Energy Futures Modeling System (EFMS) to analyze marginal generation sources. The EFMS is a collection of models and modules that are soft and/or hard linked in order to produce CER Energy Futures scenarios. For this analysis, we focus on the electricity sector, where the EFMS utilizes Python for Power System Analysis (PyPSA), an open-source power flow optimization model, to complement the electricity analysis in the EFMS's core energy system model, ENERGY2020. An overview of the EFMS and integration with PyPSA is found in [26].

PyPSA is included in the EFMS to add additional granularity, particularly greater temporal resolution, for electricity modelling. This section provides a brief overview of PyPSA. Full documentation of PyPSA is available from its website. The objective function for the optimization is comprised of total capital and generating costs for each network component and generator. Several constraints are added to generators. Minimum and maximum generation constraints for each hour along with hour-to-hour ramping constraints are added for certain technology groups. For example, the maximum hourly generation for wind and solar is determined by the site level historical wind speed and solar irradiance data. Similarly, minimum and maximum generating constraints on hydroelectricity are incorporated, based on seasonal availability. Ramping constraints are also imposed based on technology operating characteristics. For example, coal plants and nuclear reactors cannot rapidly ramp their generation up or down, while technologies like simple cycle gas turbines can quickly change generation. These differences are reflected in the ramping constraints. On the demand side, future hourly demand is simulated using a combination of historical hourly load factors and ENERGY2020's forecasted peak demand. The historical load factors are scaled up using the projected peak loads, which gives an hourly demand profile for the given year. All of the above discussed constraints and data are then fed into PyPSA to create the optimal generation profile for each province and forecast year.

The use of PyPSA is guided by the overall goal of the EFMS, which is to produce long-term scenarios. In the EFMS, PyPSA provides important insights on how the electricity system could operate at an hourly level, which is important for assessing factors such as variable renewable generation and battery storage. While PyPSA can be utilized to include more granular data (such as generators by unit or facility, or sub-hour time intervals), the focus is on broad technology groupings (wind, solar, combined cycle natural gas, simple cycle natural gas, etc.) and an hourly time interval. Because PyPSA integrates with broader energy system modelling, this level of detail provides a trade-off between realism and tractability for long-term scenario analysis.

For each time slice, the model outputs generation and a location-specific marginal price. The marginal fuel type is inferred based on the marginal price for each time slice. Emissions for each hour are computed by multiplying each fuel type's generation by the corresponding emission factor assumption for that fuel and level of output. The average emissions factor is computed by dividing the sum of emissions for each hour by the sum of generation. The marginal emissions factor is equal to the emissions output of the marginal fuel type divided by its generation.

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#### 4. Data Sources

The models discussed in Section 3 use different sets of input data which include both common and model-specific items. Sometimes, the input data are processed before being used in a model. Also, it is possible that some input data are used to further process the output of a certain model in order to evaluate a common metric. Table 1 summarizes the input data and associated sources.

This analysis focuses on the year 2018, meaning that most of the input data used by the models are recorded in 2018 except some technical information which may not need to be updated every year such as heat rate curves or operational information of different types of generators.

Note that both models consider Alberta as one zone so information such as transmission constraints and costs (intra-provincial congestion) as well as the generation and transmission network architecture are not required.

	Data Source				
Input	MLR Model	CER Model			
Hourly marginal electricity prices	AESO	[29]			
Hourly imports from all interties	AESO <sup>[30]</sup>				
Type of generator	AESO	[30]			
Heat rate curves by type of coal/gas generator (all generators)	Literature <sup>[27][28]*</sup>	AESO <sup>[30]</sup> + Literature <sup>[27][28]*</sup>			
CO <sub>2</sub> emissions per unit fuel consumption	U.S. Energy Information A	Administration (EIA) <sup>[31]</sup>			
British Columbia average annual emission factor	National Inventory Report				
Saskatchewan average annual emission factor	(NIR) <sup>[32]</sup>				
Montana intertie average annual emission factor	EIA <sup>[33]</sup>				

 Table 1: Sources for the inputs of the different models

	Data Source				
Input	MLR Model	CER Model			
Hourly output of all generators in Alberta	AESO <sup>[30]</sup>				
Hourly load <sup>*</sup>		AESO <sup>[30]</sup>			
Operational information of each type of generator (e.g. ramp, start-up cost)**		Literature <sup>[34]</sup>			
Renewable energy availability forecast		AESO <sup>[30]</sup>			

\* The heat rate curves for coal, natural gas combined cycle, and natural gas steam generators were first estimated by taking their respective curves in [27] and scaling such that their full-load heat rate values matched those provided by the EIA [28]. They were then modelled by fitting a quadratic to the resulting curves (the quadratic providing a best fit). The search for a heat-rate curve for natural gas simple-cycle generators was inconclusive; thus, a flat (constant) heat rate was used, corresponding to its full-load heat rate in [28].

\*\* Hourly constraints for ramp limits and minimum/maximum output are expressed as percentages of the total capacity for the entire generation fleet, based on AESO's unit generation data. There are no constraints for shut down and start-up costs or ramps.

#### 5. Results and Analysis

In this section, the results of the two models are discussed and compared with the data from AESO. The AESO provides the fraction of time that each generator type is marginal on an annual basis [2]. This information can be used to validate how well both models capture marginal generation. As shown in Table 2, the results of the CER model are much closer to the data from AESO than those of the MLR model, which significantly underestimates the fraction of time that coal is on the margin and overestimates the fraction of time that hydroelectric and gas generators are on the margin.

Regarding the fraction of total generation provided by each generator type, as shown in Table 3, CER model calculations are again very close to those reported by AESO. Note that the CER model was run without taking interties into account, so it naturally neglects their contribution. There are no results reported for the MLR model since it considers the generation information as a model input.

Figure 2 shows a heat map of average MEFs by hour and month for the two models (in kg of CO2/MWh) and Table 4 summarizes key statistics of these data. The average MEF heat map may serve as a guide to decide when the best time is to add a marginal load, e.g. EV charging load, to the system so that the emissions are the least. As can be seen from Figure 2, the MEFs from the MLR model have very low variability compared to those of the CER model, with MEFs from the MLR model being relatively insensitive to month and time of day. The CER model shows roughly the same hourly pattern across all months, with the lowest MEFs occurring in the morning (roughly 5:00-8:00) and afternoon (roughly 12:00-15:00). Meanwhile, the MLR model predicts lower emissions in the late evening to early morning, but the pattern is much less pronounced than for the CER model so not as apparent in the heat map. Given the

better agreement between the CER model and the available AESO data, it seems plausible that its hourly MEF pattern is closer to the reality, but this cannot be directly validated at this stage.

Generator Type	MLR Model	CER Model	AESO <sup>[2]</sup>
Coal	57%	73%	79%
Gas	35%	27%	18%
Hydroelectric	9%	0%	1%
Wind	0%	0%	0%
Other	0%	0%	1%

Table 2: Fraction of time different generator types are on the margin

Table 3: Fraction of total generation provided by different generator types

Generator Type	MLR Model	CER Model	AESO <sup>[2]</sup>
Coal		47%	45%
Gas		43%	40%
Hydroelectric		3%	3%
Wind		7%	6%
Imports			5%
Other		0%	1%

Table 4: Statistical properties of the distribution of MEFs (kg of  $CO_2/MWh$ ) in Figure 2

Parameter	MLR Model	CER Model
Minimum	681	482
Maximum	701	999
Average	693	842
Median	693	886
Standard Deviation	4	126

							Mo	nth						
		1	2	3	4	5	6	7	8	9	10	11	12	Average
	1	690	688	688	684	681	683	686	687	687	689	690	692	687
	2	690	689	688	685	683	684	688	688	687	690	691	692	688
	3	690	689	689	685	683	684	688	688	688	690	691	693	688
	4	691	690	689	686	683	684	687	689	688	690	692	694	689
	5	692	692	691	687	684	685	689	689	689	691	693	695	690
	6	694	694	693	689	685	686	689	692	691	693	695	696	691
	7	698	697	696	692	688	689	691	693	695	695	697	698	694
	ģ	600	700	697	693	692	692	694	694	695	698	698	700	696
	å	600	696	695	692	692	693	696	696	695	695	697	700	696
	10	606	606	605	601	602	602	606	607	605	605	607	600	605
	11	606	606	604	602	602	602	606	606	605	606	606	600	605
-	12	606	605	604	601	602	603	605	606	604	605	606	609	605
ō	12	696	695	602	601	692	695	695	696	694	695	690	609	695
-	14	695	604	603	601	692	602	696	696	604	604	694	698	694
	14	095	694	692	691	092	092	695	696	694	694	696	697	094
	15	695	694	692	690	691	692	695	696	694	693	696	698	694
	16	696	695	693	690	691	692	695	696	694	694	697	698	694
	17	699	697	694	691	692	693	696	696	694	695	697	701	695
	18	701	698	694	691	691	692	694	695	695	695	698	701	695
	19	697	699	694	688	689	689	693	694	693	695	696	698	694
	20	695	696	695	689	689	690	693	694	694	695	697	698	694
	21	695	694	695	691	688	689	691	694	695	693	696	698	693
	22	694	693	692	691	688	688	692	694	691	692	693	697	692
	23	691	690	689	686	686	688	692	691	688	690	692	695	690
	24	690	689	688	684	682	685	689	688	687	690	691	694	688
Aver	age	695	694	693	689	688	689	692	693	692	693	695	697	693
							MLR I	Vodel						Annual average
							Mo	nth						Ŭ
		1	2	3	4	5	<b>Mo</b> 6	nth 7	8	9	10	11	12	Average
	1	1 812	2 784	3 875	4 938	5 980	6 908	nth 7 887	8 871	9 915	10 972	11 856	12 790	Average 882
	1 2	1 812 902	2 784 760	3 875 869	4 938 959	5 980 971	Mo 6 908 941	nth 7 887 880	8 871 923	9 915 962	10 972 970	11 856 912	12 790 836	Average 882 907
	1 2 3	1 812 902 913	2 784 760 772	3 875 869 917	4 938 959 947	5 980 971 952	Mo 6 908 941 945	nth 7 887 880 865	8 871 923 926	9 915 962 961	10 972 970 914	11 856 912 915	12 790 836 939	Average 882 907 914
	1 2 3 4	1 812 902 913 896	2 784 760 772 796	3 875 869 917 806	4 938 959 947 857	5 980 971 952 911	Mo 6 908 941 945 902	nth 7 887 880 865 960	8 871 923 926 862	9 915 962 961 765	10 972 970 914 720	11 856 912 915 887	12 790 836 939 908	Average 882 907 914 856
	1 2 3 4 5	1 812 902 913 896 706	2 784 760 772 796 699	3 875 869 917 806 710	4 938 959 947 857 734	5 980 971 952 911 806	Mo 6 908 941 945 902 886	nth 7 887 880 865 960 856	8 871 923 926 862 694	9 915 962 961 765 616	10 972 970 914 720 638	11 856 912 915 887 744	12 790 836 939 908 762	Average 882 907 914 856 738
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Hour	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15	1 812 902 913 896 706 550 550 716 886 888 758 611 557 530 637	2 784 760 772 796 697 637 667 800 932 947 948 783 641 643 730	3 875 869 917 806 710 623 771 939 930 809 734 623 574 623 574 885	4 938 959 947 857 734 701 796 875 915 875 915 897 779 659 655 790 903	5 980 971 952 911 806 754 824 866 867 874 874 877 652 580 646 799	Mo 908 941 945 902 886 812 778 887 887 887 882 885 825 554 508 495 651	nth 7 887 886 960 856 739 742 841 999 980 980 980 980 941 649 941 649 572 842	8 871 923 926 862 694 621 667 784 883 941 822 726 727 633 652	9 915 962 961 765 616 655 797 918 981 942 641 621 646 782 959	10 972 970 914 720 638 658 876 957 939 848 669 593 601 754 944	11 856 912 915 887 744 638 640 816 909 930 831 693 616 554 677	12 790 836 939 908 762 737 826 922 980 867 734 679 646 683	Average 882 907 914 856 738 672 740 852 919 910 803 659 613 637 761
Hour	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16	1 812 902 913 896 706 559 716 886 888 888 888 888 611 557 530 637 889	2 784 760 772 796 637 667 800 932 947 800 932 948 783 641 643 730 847	3 875 869 917 806 710 623 771 939 930 809 930 809 734 623 <b>574</b> 691 885 5918	4 935 947 857 734 706 875 915 897 779 659 655 790 903 951	5 980 971 952 911 806 754 824 866 857 874 826 867 874 827 850 645 799 919	Mo 6 948 945 902 886 812 778 887 882 885 885 825 564 508 495 564 508 495	nth 7 887 880 865 960 886 960 886 739 742 841 999 980 984 941 649 572 482 640 934	8 871 923 926 862 664 667 784 883 941 822 726 727 633 652 780	9 915 962 961 765 616 655 797 918 981 942 641 621 646 782 959 954	10 972 970 914 720 638 658 876 957 933 848 876 957 933 848 669 593 601 754 954	11 856 912 915 887 744 640 816 909 930 831 693 615 554 677 932	12 790 836 939 908 762 662 737 826 922 980 867 734 679 646 683 8871	Average 882 907 914 856 738 672 740 852 919 910 803 659 613 637 637 761 887
Hour	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17	1 812 902 913 886 560 579 716 886 888 758 611 557 530 637 839 925	2 784 760 772 796 699 637 667 800 932 947 948 783 641 643 730 847 834	3 875 869 917 806 710 623 771 930 809 734 623 574 691 885 918	4 938 959 947 857 734 701 796 875 897 779 655 897 779 655 903 903 951 973	5 980 971 952 911 806 754 824 867 874 827 652 580 646 799 919 931	Mo 9981 945 942 886 812 778 887 887 887 887 885 885 825 825 885 825 825 825 825 825	nth 7 887 880 865 960 856 856 856 856 980 980 980 980 980 980 980 941 649 9572 2482 610 734 857 9572 9572 9572 957	8 871 923 926 862 694 621 667 784 883 941 822 726 633 652 780 929	9 915 962 961 765 616 655 797 918 942 641 621 644 644 644 646 782 959 964 974	10 972 970 914 720 638 658 876 957 957 939 848 669 939 848 669 593 601 754 944 956	11 856 912 915 887 744 638 640 816 930 831 693 615 554 677 932 957	12 790 836 939 908 762 662 737 826 920 826 920 867 734 679 646 683 871 937	Average 882 907 914 856 738 672 740 852 919 910 803 659 613 637 761 887 934
Hour	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18	1 812 902 913 886 550 579 716 886 888 758 611 557 530 637 819 925 937	2 784 760 772 669 637 667 800 932 947 800 932 948 783 641 643 730 847 834 730	3 875 869 917 806 623 7710 623 939 930 809 930 809 734 623 574 623 574 691 885 918 885 918	4 938 959 947 734 701 796 875 915 875 915 877 779 659 655 7900 655 903 951 973	5 980 971 952 911 806 754 826 866 867 874 827 652 580 646 62 580 649 919 931 934	Mo 908 941 945 902 886 812 778 887 887 885 825 554 554 554 554 555 651 889 941	nth 87 880 885 960 856 739 742 841 999 980 941 649 941 841 841 841 841 841 841 841 8	8 871 923 926 862 664 667 784 883 941 822 726 727 633 652 780 929 957	9 915 962 961 765 616 655 981 981 981 982 641 621 646 782 959 964 973	10 972 970 914 720 638 658 876 957 939 848 669 593 601 754 944 954 954 957	11 856 912 915 887 744 638 640 816 909 930 831 693 616 554 677 932 967 954	12 790 836 933 966 762 662 737 826 922 980 867 734 679 646 683 871 933	Average 882 907 914 856 738 672 740 852 919 910 803 659 633 659 613 637 751 887 934 934
Hour	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19	1 812 902 913 896 560 579 716 886 888 888 611 557 530 637 819 925 937	2 784 760 772 6699 637 667 800 932 947 947 948 783 641 643 730 847 834 834 834	3 875 869 917 806 623 7710 623 771 930 930 930 930 930 930 930 623 574 601 865 574 601 865 918 917 917 907	4 938 959 947 734 701 796 875 915 915 897 7790 659 655 790 903 951 973 973	5 980 971 952 911 806 754 866 867 874 827 652 580 646 799 919 931 954 978	Mo 6 908 941 945 902 886 812 778 882 885 825 845 564 508 495 651 889 944 964 974	nth 7 887 880 8865 960 8856 739 742 841 999 980 941 649 572 482 610 794 915 954 954	8 871 923 926 862 664 621 667 784 883 941 823 726 727 633 652 727 633 652 780 929 957	9 915 962 961 765 616 655 797 918 981 942 641 621 646 782 959 964 974 953	10 972 970 914 720 638 658 876 957 939 848 669 593 601 754 954 954 954 960 972	11 856 912 915 887 744 638 640 816 909 930 831 693 616 554 677 932 967 955	12 790 836 939 908 762 662 737 826 662 922 980 867 734 679 646 683 871 937 937 939	Average 882 907 914 855 738 672 740 852 919 910 803 653 659 613 637 761 887 934 940 947
Hour	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20	1 812 902 913 813 570 570 570 716 886 886 886 886 886 557 530 637 819 925 937 930	2 784 760 772 966 800 932 947 830 643 643 643 730 847 834 847 834 834 822 821	3 875 869 917 806 710 623 939 930 809 734 623 574 623 574 691 885 918	4 938 959 947 734 701 796 875 875 915 877 779 659 659 659 659 903 903 903 951 973 973	5 980 971 952 911 806 754 866 867 874 877 652 580 646 799 911 931 954 978	Mo 6 904 945 942 885 887 887 887 887 887 887 885 885	nth 7 887 880 855 960 856 739 742 841 999 980 941 649 941 649 941 572 649 941 572 954 954 954 954 954	8 871 923 926 862 664 621 667 784 883 941 822 726 727 633 652 780 929 957 957	9 915 962 961 765 616 655 918 981 942 641 621 646 41 621 646 782 959 964	10 972 970 914 720 638 658 875 957 933 848 8669 <b>593</b> 601 754 944 954 954 956 972 960 972 960	11           856           912           915           887           744           638           640           818           909           930           831           693           656           554           677           952           954	12 790 836 939 908 762 662 737 826 922 980 867 734 679 646 683 871 937 930 949	Average 882 907 914 856 738 672 740 852 919 910 803 659 613 637 761 887 934 940 947 942
Hour	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21	1 812 902 913 896 560 570 688 888 688 688 555 611 557 530 637 819 925 937 947 930	2 784 760 772 796 637 667 800 932 948 783 641 641 641 641 643 730 847 834 730 847 832 821 833	3 875 869 917 806 623 7710 623 930 809 734 623 574 623 574 623 574 885 918 885 918 917 907 917	4 938 959 947 734 701 796 875 915 875 915 877 779 659 655 790 903 951 973 973 972 973	5 980 971 952 911 806 754 826 866 867 874 827 652 580 646 652 580 645 979 919 931 934 978 978	Mo 6 941 945 902 886 812 778 887 882 887 862 885 564 508 495 651 888 944 508 495 651 888 944 955	7           887           880           865           960           885           986           887           739           742           841           999           980           941           649           572           482           610           794           953           954           964           928	8 871 923 926 862 664 621 667 784 883 941 822 726 727 633 652 727 633 652 780 929 957 968 957	9 915 962 961 765 616 655 981 981 981 982 641 621 646 782 959 964 974 953 961 953	10 972 970 914 720 638 658 876 957 939 848 669 <b>593</b> 601 754 954 954 954 959 959	11           856           912           915           87           744           638           640           816           909           930           616           554           677           932           967           954           965           954           965	12 790 836 933 752 662 737 826 922 980 867 734 679 646 633 871 937 930 949 949	Average 882 907 914 856 738 672 740 852 919 910 803 659 633 659 633 659 633 637 761 887 934 934 940
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лон	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 age	1 812 902 913 856 856 579 716 886 888 637 550 637 550 637 819 925 937 937 947 930 922 937 947 930 920 920 920 920 920 920 920	2 784 760 772 669 800 932 948 783 641 643 643 643 847 834 822 821 834 832 831 838 831 838 831 832 831	3 875 869 917 806 710 623 939 930 809 809 734 623 574 623 574 631 885 918 885 917 917 917 917 917 917 929 938 929 938	4 938 959 947 734 701 796 875 915 875 915 875 915 897 779 903 953 973 973 973 973 973 973 973 973 973 97	5 980 971 952 952 806 754 866 867 874 827 652 580 646 646 799 911 954 978 978 978 978 978 874	Mo 6 908 941 945 825 887 887 887 887 885 885 825 564 495 651 889 944 961 974 955 954 825 825 825 825 825 825 825 825	nth 7 880 880 855 856 856 841 999 841 999 980 941 649 941 649 941 649 941 942 954 954 954 954 955 955 925 925 925 925 926 926 926 926 926 926 926 927 928 928 928 928 928 928 928 928 928 928	8 871 923 926 862 664 621 667 784 883 941 822 726 727 633 652 780 957 963 957 965 957 949 957 949	9 915 962 961 765 616 655 797 918 981 941 646 782 959 964 974 953 964 974 953 964 974 953 964 974 953 962 974 954 954	10 972 970 914 720 638 658 875 957 938 669 593 601 754 954 954 954 955 955 955 955 955 955 9	11           856           912           915           815           640           818           909           930           831           693           654           677           932           957           954           965           955           954           965           955           955           955           955           955           951           802           832	12 790 836 933 908 762 662 737 826 922 980 867 734 679 646 683 871 930 949 949 949 949 949 949	Average 823 907 914 856 738 672 740 852 919 910 833 659 613 637 637 637 637 637 934 940 947 942 940 947 942 940 945 920 884 884 842 Annual average

Figure 2: Average MEFs by hour and month for the two models (kg of CO<sub>2</sub>/MWh)

Figure 3 shows heat maps of AEFs by hour and month from the CER model, and derived directly from AESO generator output data using the heat rate curves and CO2 content assumptions from Table 1. In both cases, the main variations occur across months rather than across hours, with lowest AEFs during the early summer (May and June) and highest AEFs during shoulder months (March and September). The variability of the AEF values in both cases is comparable and much lower than for the CER MEFs, as shown in Table 5.

						Mo	nth						
	1	2	3	4	5	6	7	8	9	10	11	12	Average
1	649	633	676	632	591	609	663	671	695	681	679	671	654
2	646	627	672	629	588	604	667	670	698	684	678	669	653
3	645	624	671	628	589	600	670	672	703	684	675	671	653
4	643	624	671	627	591	597	671	673	706	685	676	672	653
5	647	624	673	627	590	597	671	672	705	685	679	672	654
6	650	624	673	628	588	601	669	673	705	681	675	672	654
7	660	626	681	635	587	608	670	676	704	675	672	665	655
8	659	629	682	631	588	607	660	665	692	660	658	655	649
9	668	636	683	640	600	619	667	670	688	658	662	656	654
10	669	640	683	638	604	624	672	678	689	656	663	658	656
11	663	647	682	644	602	628	668	676	689	662	665	658	657
5 12	661	646	679	648	608	631	664	673	686	663	666	659	657
± 13	661	650	681	652	615	629	665	673	683	659	665	659	658
14	657	649	678	653	618	627	661	670	679	658	666	659	656
15	654	651	675	650	618	623	660	666	679	653	667	659	655
16	652	649	674	649	617	621	655	663	6/9	651	668	656	653
1/	650	648	6/1	647	618	620	656	664	6//	651	660	651	651
18	652	647	670	646	618	615	652	661	680	652	656	652	650
19	654	651	669	643	618	608	653	663	682	652	659	650	650
20	652	650	669	640	615	607	648	003	684	652	664	649	650
21	654	647	673	640	602	609	644	665	684	660	660	650	649
22	650	620	677	643	503	610	640	664	691	664	609	653	652
25	650	636	676	636	590	614	652	669	600	674	672	661	650
24 Avorago	654	620	675	620	602	612	661	660	699	665	669	660	652
Average	0.04	035	0/5	035	005	Derived f		005	090	005	008	000	Annual average
						Mo	nth						, and a verage
	1	2	3	4	5	6	7	8	9	10	11	12	Avorago
													Average
1	638	664	651	620	604	597	621	625	627	620	634	638	628
1	638 637	664 664	651 650	620 617	604 601	597 590	621 612	625 621	627 628	620 620	634 632	638 634	628 626
1 2 3	638 637 634	664 664 665	651 650 654	620 617 618	604 601 597	597 590 587	621 612 605	625 621 618	627 628 628	620 620 617	634 632 629	638 634 629	628 626 623
1 2 3 4	638 637 634 631	664 664 665 663	651 650 654 656	620 617 618 619	604 601 597 590	597 590 587 585	621 612 605 602	625 621 618 614	627 628 628 629	620 620 617 617	634 632 629 624	638 634 629 625	628 626 623 621
1 2 3 4 5	638 637 634 631 626	664 664 665 663 661	651 650 654 656 652	620 617 618 619 610	604 601 597 590 580	597 590 587 585 576	621 612 605 602 601	625 621 618 614 609	627 628 628 629 622	620 620 617 617 610	634 632 629 624 616	638 634 629 625 621	628 626 623 621 615
1 2 3 4 5 6	638 637 634 631 626 617	664 665 663 661 655	651 650 654 656 652 646	620 617 618 619 610 601	604 601 597 590 580 576	597 590 587 585 576 576 574	621 612 605 602 601 600	625 621 618 614 609 603	627 628 628 629 622 615	620 620 617 617 610 602	634 632 629 624 616 607	638 634 629 625 621 613	628 626 623 621 615 609
1 2 3 4 5 6 7	638 637 634 631 626 617 606	664 665 663 661 655 647	651 650 654 656 652 646 636	620 617 618 619 610 601 590	604 601 597 590 580 576 565	597 590 587 585 576 576 574 566	621 612 605 602 601 600 594	625 621 618 614 609 603 593	627 628 628 629 622 615 605	620 620 617 617 610 602 592	634 632 629 624 616 607 601	638 634 629 625 621 613 610	628 626 623 621 615 609 600
1 2 3 4 5 6 7 8	638 637 634 631 626 617 606 597	664 665 663 661 655 647 642	651 650 654 656 652 646 636 630	620 617 618 619 610 601 590 582	604 601 597 590 580 576 565 565 561	597 590 587 585 576 574 566 558	621 612 605 602 601 600 594 585	625 621 618 614 609 603 593 582	627 628 629 622 615 605 597	620 620 617 617 610 602 592 587	634 632 629 624 616 607 601 593	638 634 629 625 621 613 610 606	628 626 623 621 615 609 600 593
1 2 3 4 5 6 7 8 9	638 637 634 631 626 617 606 597 592	664 665 663 661 655 647 642 636	651 650 654 656 652 646 636 630 626	620 617 618 619 610 601 590 582 578	604 601 597 590 580 576 565 561 559	597 590 587 585 576 574 566 558 558 556	621 612 605 602 601 600 594 585 583	625 621 618 614 609 603 593 582 575	627 628 629 622 615 605 597 595	620 620 617 617 610 602 592 587 584	634 632 629 624 616 607 601 593 583	638 634 629 625 621 613 610 606 599	628 626 623 621 615 609 600 593 589
1 2 3 4 5 6 7 8 9 10	638 637 634 631 626 617 606 597 592 590	664 665 663 661 655 647 642 636 632	651 650 654 656 652 646 636 630 626 626	620 617 618 619 610 601 590 582 578 580	604 601 597 590 580 576 565 561 559 561	597 590 587 585 576 574 566 558 556 556 556	621 612 605 602 601 600 594 585 583 583 582	625 621 618 614 609 603 593 582 575 576	627 628 629 622 615 605 597 595 598	620 620 617 617 610 602 592 587 584 584 587	634 632 629 624 616 607 601 593 583 579	638 634 629 625 621 613 610 606 599 597	628 626 621 615 609 600 593 589 589
1 2 3 4 5 6 7 8 9 10 11	638 637 634 631 626 617 606 597 592 590 593	664 665 663 661 655 647 642 636 632 629	651 650 654 656 652 646 636 630 626 626 626 622	620 617 618 619 610 601 590 582 578 580 585	604 601 597 590 580 576 565 561 559 561 563	597 590 587 585 576 574 566 558 556 556 556 556	621 612 605 602 601 600 594 585 583 582 583 582	625 621 618 614 609 603 593 582 575 576 576 579	627 628 629 622 615 605 597 595 598 607	620 620 617 617 610 602 592 587 584 587 584 587	634 632 629 624 616 607 601 593 583 579 582	638 634 629 625 621 613 610 606 599 597 597 599	628 626 623 621 615 609 600 593 589 589 589
1 2 3 4 5 6 7 8 9 10 11 11 12	638 637 634 631 626 617 606 597 592 590 593 605	664 665 663 661 655 647 642 636 632 629 631	651 650 654 656 652 646 636 630 626 626 632 639	620 617 618 619 610 601 590 582 578 580 585 585 585 585	604 601 597 590 580 576 565 561 559 561 563 563 569	597 590 587 585 576 574 566 558 556 556 556 556 556 552	621 612 605 602 601 600 594 585 583 582 583 582 585 585 582	625 621 618 614 609 603 593 582 575 576 579 586 579	627 628 628 629 622 615 605 597 595 598 607 619	620 620 617 617 610 602 592 587 584 587 584 587 596 606	634 632 629 624 616 607 601 593 583 579 582 582 590	638 634 629 625 621 613 610 606 599 597 599 605	628 626 623 621 615 609 600 593 589 589 589 589
1 2 3 4 5 6 7 8 9 10 11 11 12 13	638 637 634 631 626 617 606 597 592 590 593 605 617	664 665 663 661 655 647 642 636 632 629 631 636	651 650 654 656 652 646 636 630 626 626 626 632 639 646	620 617 618 619 610 601 590 582 578 580 585 593 600	604 601 597 590 580 576 565 561 559 561 563 563 569 577	597 590 587 585 576 574 566 558 556 556 556 556 556 552 571 581	621 612 605 602 601 594 585 583 583 582 583 582 585 592 603	625 621 618 614 609 603 593 593 575 576 579 586 597	627 628 629 622 615 605 597 595 598 607 619 625	620 620 617 617 610 602 592 587 584 587 584 587 596 606 612	634 632 629 624 616 607 601 593 583 579 582 590 599	638 634 629 625 621 613 610 606 599 597 599 605 614	628 626 623 621 615 609 600 533 589 589 589 589 589 601 609
1 2 3 4 5 6 7 8 9 10 11 11 12 13 14	638 637 634 626 617 606 597 592 590 593 605 617 624	664 665 663 661 655 647 642 636 632 629 631 636 638	651 650 654 656 652 646 630 626 630 626 632 639 646 652	620 617 618 619 610 601 590 582 578 580 585 593 600 604	604 601 597 590 580 576 565 561 569 561 563 569 577 581	597 590 587 585 576 574 566 558 556 556 556 556 556 556 556 556	621 612 605 602 601 600 594 585 583 583 582 585 592 603 608	625 621 618 614 609 603 593 582 575 576 579 586 597 599	627 628 629 622 615 605 597 595 598 607 619 625 624	620 620 617 617 610 602 592 587 584 587 584 587 596 606 612 611	634 632 629 624 616 607 601 593 583 593 583 579 582 590 599 604	638 634 629 625 621 613 610 606 599 597 597 599 605 614 618	628 626 623 621 615 609 600 593 589 589 589 589 593 601 609 601
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15	638 637 634 631 626 617 606 597 592 593 605 617 624 627	664 665 663 661 655 647 642 636 632 629 631 636 638 642	651 650 654 655 646 636 630 626 630 626 632 639 646 652 652 652	620 617 618 619 610 601 590 582 578 580 585 585 585 585 600 604 614	604 601 597 590 580 576 565 561 559 561 563 569 577 581 597	597 590 587 585 576 574 566 558 556 556 556 556 556 552 571 581 587 601	621 612 605 602 601 600 594 585 583 582 585 592 603 608 622	625 621 618 614 609 603 593 582 575 576 579 586 597 599 613	627 628 628 629 622 615 605 597 595 598 607 619 625 624 629	620 620 617 617 610 602 592 587 584 587 596 606 612 611 619	634 632 629 624 616 607 601 593 583 579 582 599 604 608	638 634 629 625 621 613 610 606 599 597 599 605 614 618 618 618	628 628 626 623 621 615 609 600 593 589 589 589 589 589 589 601 609 612 621 621
1 2 3 4 5 6 7 8 9 10 11 11 13 14 15 16	638 637 634 631 626 617 606 597 592 590 593 605 617 624 627 639	664 665 663 661 655 647 642 636 632 632 632 632 633 642 651 651	651 650 654 655 652 646 636 626 626 626 632 639 646 652 658 660	620 617 618 619 610 601 590 585 578 580 585 593 600 604 614 618	604 601 597 590 580 576 565 561 563 563 569 577 581 597 599	597 590 587 585 576 574 566 556 556 556 556 562 571 581 587 601 606	621 612 605 602 601 600 594 585 583 582 585 582 585 592 603 608 622 631	625 621 618 614 609 603 593 585 575 576 579 586 579 586 599 613 627	627 628 629 622 615 605 597 595 598 607 619 625 624 629 634	620 620 617 617 610 602 592 587 584 587 596 606 611 619 623	634 632 629 624 616 607 601 593 583 579 582 590 599 604 608 617	638 634 629 625 621 613 610 606 599 597 599 605 614 618 618 618 625	628 628 623 621 615 609 600 593 589 589 589 589 589 589 593 601 609 612 621 627 621
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Figure 3: AEFs by hour and month estimated from AESO data and the CER model (kg of CO<sub>2</sub>/MWh)

Table 5: Statistical	properties	of the distrib	oution of AFFs	(kg of	CO <sub>2</sub> /MWh)	in Figure	З
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Parameter	MLR Model	CER Model
Minimum	587	556
Maximum	706	668
Average	653	617
Median	658	620
Standard Deviation	26	25

#### 6. Discussion

In this analysis, two approaches have been used to estimate marginal emission factors for Alberta in 2018. Each can provide useful policy-applicable insights on the dynamics of marginal emission factors in a given province for its grid at a given point in time. For example, if marginal emissions factors are typically lower during certain hours of the day, policies to encourage load shifting to those hours could realize some emission reductions.

With respect to future decarbonisation pathways, the MLR model differs from the CER model in that it is solely focusing on current/historical analysis. The CER model has the ability to provide outlooks for future years, and in fact, this is their most common use case. When similar MEF analysis is done for a future year for these models, it will be done by analyzing the marginal generator in that future electricity system, which could have significantly different characteristics compared to today in areas such as load, load shape, generation technology mix, or trade. In the context of deep decarbonisation pathway analysis, much of the attention and interest are on non-marginal changes, such as electrifying personal transportation or space heating, or decarbonising the electricity generation mix. Therefore, the estimated MEF in a future year represents a marginal change in that future energy system, not the change from current conditions to that future system, which could be large.

Both modelling techniques rely on detailed historical data for parameters such as load, generation, trade, and prices. Data availability is one of the key reasons we have focused on Alberta in this analysis. Availability of data is a critical component for similar analysis to be done for other regions. In some cases, simplifying assumptions could be made where data is not available (such as applying load shapes from a neighbouring or similar region), but could possibly undermine the accuracy and policy relevance of the analysis. Other regions may have unique characteristics that should be considered. For example, analysis such as [35] and [36] focus on jurisdictions with large hydro resources. In these studies, the operational characteristics of hydro facilities are particularly important.

There would definitely be benefits in integrating the different models presented in this report in a national modelling platform as these could be used for future projects of Canadian electricity systems. Their assumptions and limitations would have to be clearly stated, however, so these are not used beyond their capabilities. The main challenge would be in providing publicly available input data for all Canadian provinces and territories. Such data would be very valuable especially if sources are identifiable and estimations and assumptions are vetted by experts in the field.

### 7. Future Work

As an immediate next step, the comparison proposed in this report will be expanded to cover more provinces starting with Ontario as most of the input data required will be readily available from the Independent Electricity System Operator (IESO). Other models providing outputs that can be used to compute metrics such as average and marginal emission factors will also be investigated. This includes various open-source unit commitment and dispatch (UC&D) models such as the SILVER model developed by the University of Victoria in British Columbia and the E3 RESOLVE model. Unit Commitment and Dispatch approaches have several applications beyond marginal emission factors calculation. In addition, these models are critical to consider in the planning stage to ensure that solutions are feasible – especially given changes in load characteristics from electrification and increased adoption of variable renewables. In the context of larger planning exercises, it will feed into other power system models as well as other applications models, taking their output as input and vice versa.

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