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Carbon Emission Pinch Analysis for Regional Planning of Rural Electrification

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Rural electrification is an ongoing issue in Sarawak, a state in East Malaysia. About 7 % of Sarawak's rural population is still inaccessible to electricity. However, adding more fossil fuel resources to electrify Sarawak fully will result in increased carbon emissions. This will contradict Malaysia's plans to reduce 45 % of carbon dioxide emission from 2010 levels by 2030. Therefore, low carbon energy resources must be deployed to meet rising energy demands in rural areas. Before deploying these energy resources, it is necessary to determine minimum targets to achieve carbon emission reductions. This can be planned via carbon emission pinch analysis (CEPA). Thus, this study presents a regional planning model built upon CEPA that would assist in optimising the energy generation planning and the technical selection of energy generation technologies. This study will also analyse the usage of low carbon energy resources considering the carbon emission reduction targets to meet electrical demands in rural communities. An energy planning case study for a region in Malaysia, known as Sarawak, is solved to illustrate the carbon emission pinch analysis method. The results from the case study show that the consumption of carbon-intensive resources reduces when the additional capacity for new low carbon resources is allowed in the model. As a result, the consumption of coal, natural gas and diesel in 2040 has reduced to 4,449,151 MWh, 24, 673,913 MWh and 480,074 MWh, respectively, compared to the consumption in 2020.

1. Introduction

Electricity has become an essential necessity to human life. As of 2019, 10 % of the world's population (i.e., 771 million people) do not have access to electricity, particularly those in rural areas (IEA, 2020). This is evident within rural regions in Malaysia. Sarawak, a region in Malaysia, is the largest state in Malaysia, with a population of 2,907,500 (Sarawak Government, 2020). According to the latest data in 2020 from Sarawak's local utility company (i.e., Sarawak Energy), the electricity coverage within rural populations in Sarawak is at 93 %. The remaining 7 %, which consists of 22,000 households, are still inaccessible to the state grid in 2020 (Sarawak Energy, 2020a). Under normal circumstances, it would be typical to deploy centralised power plants to address the issue. However, centralised power plants would require a high cost to establish connections in remote locations. In this sense, regional renewable energy resources available (such as biomass, solar, and hydropower energy) would provide an opportunity for decentralised electrification. Such an approach is comparatively more cost-effective, sustainable and cleaner when compared to the centralised power plants. However, renewable energy resources must be planned and deployed systematically. This can be done through regional energy planning. Regional energy planning can allocate renewable energy resources for a given region (Zhao et al., 2021).

Regional energy planning is crucial because it directly involves the regional energy requirements, energy consumption and the regionally available energy resources (Chen et al., 2015). It also assists in planning realistic targets to achieve specific national energy policies (Chen et al., 2015). Regional energy planning is most commonly done based on modelling and decision frameworks (Shah et al., 2020). There are several works previously conducted on regional energy planning models. Li et al. (2019) proposed a mixed-integer programming model and optimization framework for multi-regional energy planning. This study addresses multi-period production capacity planning of coal supply system in China (Li et al., 2019). Tan et al. (2021) built a

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modelling framework for regional power planning to optimise the energy-water-emission nexus. The framework used in this work was used to decide between economic and environmental goals in regional power planning (Tan et al., 2021). A stochastic programming model was developed for regional energy planning under electricity demand uncertainty (Irawan et al., 2021). The model was used for a long-term planning horizon to minimise the total cost when determining the timing and the technology options for energy systems (Irawan et al., 2021). However, these planning models did not consider carbon reduction targets when planning for renewable energy resources.

Prescribing a carbon emission limit while planning a renewable/low-carbon energy system can help a region reduce its emission at a reasonable rate by looking at deploying renewable resources. In this sense, carbon emission pinch analysis (CEPA) method is a promising method for regional energy planning. CEPA is a tool that can be used to plan and allocate low carbon energy sources to energy systems while meeting a certain amount of energy demand requirements and carbon emission reduction targets (Tan and Foo, 2007). CEPA is widely used for national-level energy planning and other industries. Tan et al. (2017) developed a methodology that links CEPA with Input-Output Analysis that can be used for economy-wide national or regional energy planning. The Input-Output Analysis is used together with CEPA in this work to connect carbon reduction targets to demand-side considerations (Tan et al., 2017). It is crucial to keep in mind that a mathematical alternative to the graphical version is also available (Tan and Foo, 2007). A method that integrates P-graph with CEPA was proposed for regional energy planning (Mu et al., 2020). CEPA was used to reduce the complexity of the P-graph for the raw material management network (Mu et al., 2020). Previous works show that CEPA is used along with other methods to enhance results. It can also be observed that these works did not include temporal scales and are solely based on the energy resources and energy demand in a steady-state scenario. In this study, a model is presented based on the concept of CEPA that would assist in optimising the energy generation planning, the technical selection of energy generation technologies, and the usage of low carbon energy resources. The novelty of this work is as follows: a) this model incorporates the carbon emission reduction targets to evaluate the impact of carbon limits on the additional low carbon resource target and b) this model also includes temporal scale for the long-term energy planning in order to meet electrical demands in rural communities.

2. Methodology

The first step in this work is to collect all relevant data of the interested region. This includes the available energy resources, the energy demand of the selected region, carbon emission factors of energy resources and the projection of long-term development planning. These data are usually available in the region's official websites or archives from the local ministry or the local utility companies. The following step is to formulate the mathematical model based on CEPA. CEPA is a conceptual tool used to determine targets. These targets will then be used in the network design stage, where network optimisation is done considering detailed costing. This, however, is beyond the scope of this work. The mathematical model for this work is presented as follows: The sets *i*, *j* and *t* represent the indexes for energy source, energy demand and time. Several constraints need to be included in the model. The energy balance of the energy source *i* is shown in Eq(1). $S_{i,t}$ is the maximum available capacity of energy source *i* at time *t* in MWh, $W_{i,t}$ is the unused portion of energy source *i* capacity at time *t* in MWh and $Esup_{i,j,t}$ is the energy supplied from source *i* to demand *j* at time *t* in MWh.

$$\sum_{j=1}^{J} Esup_{i,j,t} + W_{i,t} = S_{i,t} \qquad \forall i \forall t \tag{1}$$

The energy balance of energy demand *j* is shown in Eq(2). $D_{j,t}$ is the energy demand *j* at time *t* in MWh and $F_{j,t}$ is the additional low carbon resources required to meet the energy demand *j* at time *t* in MWh. $F_{j,t}$ is the low carbon resources required to decarbonise emissions according to the specified carbon reduction limits in Eq(4).

$$\sum_{i=1}^{I} Esup_{i,j,t} + F_{j,t} \geq D_{j,t} \qquad \forall j \forall t \tag{2}$$

Eq(3) below shows the equation for the consumption of energy source *i* at time *t* ($Scons_{i,t}$) where $Eff_{i,t}$ is the efficiency factor of the energy source *i* at time *t*.

$$\frac{\sum_{j=1}^{J} Esup_{i,j,t}}{Eff_{i,t}} = Scons_{i,t} \qquad \forall i \forall t \tag{3}$$

The emission limit constraint of energy demand *j* is shown in Eq(4) where $Cout_{i,t}$ is the carbon emission factor of energy source *i* at time *t* in tCO_2eq/MWh and $Cin_{j,t}$ is the carbon emission limit factor (or the carbon reduction limit) of energy demand *j* at time *t* in tCO_2eq/MWh.

$$\sum_{i=1}^{I}\left(Cout_{i,t} \times Esup_{i,j,t}\right) \leq D_{j,t} \times Cin_{j,t} \qquad \forall j \forall t \tag{4}$$

Minimum capacity constraint of energy source *i* at time *t* is shown in Eq(5) where $y_{i,t}$ is the fraction of minimum capacity in each time *t*. The purpose of this fraction is to prevent any power plants (i.e., energy sources) from shutting down immediately due to favourable carbon emission factor.

$$\sum_{j=1}^{J} Esup_{i,j,t} \geq S_{i,t} \times y_{i,t} \qquad \forall i \forall t \tag{5}$$

The variables in the model are all non-negative:

$$F_{j,t}, W_{i,t}, Esup_{i,j,t}, Scons_{i,t} \geq 0 \qquad \forall i \forall j \forall t \tag{6}$$

Finally, the objective function of this model is to minimise the additional low carbon resource required to meet the energy demand *j* at time *t* ($F_{j,t}$) as shown in Eq(7). Minimising the additional low carbon resource will allow decision-makers to determine the minimum target required to achieve the carbon reduction limit. Once the target is determined, the exact low carbon resources (i.e., solar or biomass) and cost will be determined in the network design stage.

$$\min \sum_{j=1}^{J}\sum_{t=1}^{T} F_{j,t} \tag{7}$$

3. Case study

In this work, the rural electrification issue in Sarawak is used as a case study. Based on the equations formulated in the previous section, a linear programming (LP) model was developed for this case study. The data required to solve the mathematical model were obtained from Sarawak Energy's Annual & Sustainability Report 2019 (Sarawak Energy, 2020b) and Sarawak Energy's online archives (Sarawak Energy, 2021). This case study aims to plan for a long-term renewable energy deployment and reduce CO_2 emissions in Sarawak. The planning horizon considered for this case study is 2016 – 2040. The temporal scale used in the model is five years. Note that the values in all tables represent the results at the end of each five years (i.e., 2020, 2025, 2030, 2035 and 2040). There were several assumptions made while tabulating the input data for the model:

- Electricity generating power plants operates for 8,000 h annually.
- The efficiency factors are assumed to remain constant throughout the planning horizon unless new technologies are introduced into a given power plant.
- The energy demand for the upcoming time periods was estimated using the projected values where the rural energy demands have been factored in with the overall energy demand trend (Sarawak Energy, 2017). For example, the energy demand is expected to increase by 36.6 % from 2020 to 2025 and by 7.1 % for consecutive time periods. The data obtained from Sarawak Energy's Annual & Sustainability Report 2019 are used only for the first time period (i.e., 2020).
- The emission limit factors and fractions for minimum capacity are hypothetical values.

The energy source *i* in this case study represents the coal (C), natural gas (NG), diesel (D) and hydro (H) power plants currently operating in Sarawak. The maximum available capacity of energy source *i* for all time period *t* is shown in Table 1. It should be noted that certain values for $S_{i,t}$ may be larger in later time periods compared to the ones prior. For example, the $S_{i,t}$ value for NG plants for the time period 2025 (i.e., 2021-2025) in Table 1 is larger compared to the previous time period. This is because two new combined-cycle blocks are expected to be commissioned by 2021, according to Sarawak Energy. In addition, a new hydropower plant is currently under construction and expected to commence operation in 2026. Therefore, the $S_{i,t}$ value tabulated in Table 1 for H is inclusive of the new plant from the 2030 (i.e., 2026-2030) time period onwards. The carbon emission factors, efficiencies and fractions of minimum capacity of energy source *i* at time *t* are shown in Table 2.

Table 2 is tabulated in detail for each energy source for accuracy in data. In Table 2, carbon emission factors are only tabulated for coal, natural gas and diesel plants. This is because hydropower plants have reportedly negligible net carbon emissions. Note that the difference in emission factor for the same fuel source originates from the unique efficiencies in each power plant. The efficiency factor in Table 2 (I) is the energy generation efficiency of energy source i. Note that the efficiency factor of hydropower plants (such as H Plant 1, H Plant 2, H Plant 3 and H Plant 4) is not in % and is shown as water consumed per energy generation. The minimum capacity fractions in Table 2 (II) for C Plant 4, NG Plant 2 and H Plant 4 are 1.0 for two consecutive time periods. This is because these power plants are relatively new compared to others and should be expected to operate for several years under full capacity.

Table 1: Maximum available capacity of energy source i at time t (in years) in MWh.

Energy Source (*i*)	Year (*t*) 2020	2025	2030	2035	2040
Coal (C)	4,268,233	4,268,233	4,268,233	4,268,233	4,268,233
Natural Gas (NG)	3,313,181	9,921,181	9,921,181	9,921,181	9,921,181
Diesel (D)	167,679	168,769	169,129	168,479	168,929
Hydropower (H)	21,500,228	21,500,228	31,780,228	31,780,228	31,780,228
Total $S_{i,t}$	29,249,321	35,858,411	46,138,771	46,138,121	46,138,571

Table 2: (I) Efficiency factor of energy source i at time t (in years) in MWh/m^3 (×10^4) for hydropower and % for the rest of the plants, and (II) Fraction of minimum capacity of energy source i at time t (in years), with carbon emission factor of energy source i in tCO_2eq/MWh.

Energy Source (*i*)	Emission Factor (tCO_2eq/MWh)	Year (*t*) 2020 (I)	2020 (II)	2025 (I)	2025 (II)	2030 (I)	2030 (II)	2035 (I)	2035 (II)	2040 (I)	2040 (II)
C Plant 1	1.093	30.72 %	1.00	30.72 %	0.60	30.72 %	0.50	30.72 %	0.40	30.72 %	0.30
C Plant 2	1.227	27.25 %	1.00	27.25 %	0.60	27.25 %	0.50	27.25 %	0.40	27.25 %	0.30
C Plant 3	0.910	35.57 %	1.00	35.57 %	0.60	35.57 %	0.50	35.57 %	0.40	35.57 %	0.30
C Plant 4	1.045	31.90 %	1.00	31.90 %	1.00	31.90 %	0.60	31.90 %	0.50	31.90 %	0.40
NG Plant 1	0.443	40.25 %	1.00	40.25 %	0.60	40.25 %	0.50	40.25 %	0.40	40.25 %	0.30
NG Plant 2	0.832	21.22 %	1.00	28.11 %	1.00	28.11 %	0.80	28.11 %	0.70	28.11 %	0.60
NG Plant 3	1.001	21.28 %	1.00	21.28 %	0.60	21.28 %	0.50	21.28 %	0.40	21.28 %	0.30
D Plant 1	1.212	22.14 %	1.00	22.14 %	0.60	22.14 %	0.50	22.14 %	0.40	22.14 %	0.30
D Plant 2	0.740	34.69 %	1.00	34.69 %	0.60	34.69 %	0.50	34.69 %	0.40	34.69 %	0.30
D Plant 3	0.745	34.40 %	1.00	34.40 %	0.60	34.40 %	0.50	34.40 %	0.40	34.40 %	0.30
D Plant 4	0.744	22.14 %	1.00	22.14 %	0.40	22.14 %	0.30	22.14 %	0.20	22.14 %	0.10
D Plant 5	0.914	22.14 %	1.00	22.14 %	0.60	22.14 %	0.50	22.14 %	0.40	22.14 %	0.30
D Plant 6	0.801	22.14 %	1.00	22.14 %	0.60	22.14 %	0.50	22.14 %	0.40	22.14 %	0.30
D Plant 7	0.933	22.14 %	1.00	22.14 %	0.60	22.14 %	0.50	22.14 %	0.40	22.14 %	0.30
D Plant 8	0.713	22.14 %	1.00	22.14 %	0.60	22.14 %	0.50	22.14 %	0.40	22.14 %	0.30
D Plant 9	1.138	22.14 %	1.00	22.14 %	0.60	22.14 %	0.50	22.14 %	0.40	22.14 %	0.30
D Plant 10	0.896	22.14 %	1.00	22.14 %	0.60	22.14 %	0.50	22.14 %	0.40	22.14 %	0.30
D Plant 11	0.977	22.14 %	1.00	22.14 %	0.60	22.14 %	0.50	22.14 %	0.40	22.14 %	0.30
D Plant 12	0.848	22.14 %	1.00	22.14 %	0.60	22.14 %	0.50	22.14 %	0.40	22.14 %	0.30
D Plant 13	0.917	22.14 %	1.00	22.14 %	0.60	22.14 %	0.50	22.14 %	0.40	22.14 %	0.30
D Plant 14	0.882	22.14 %	1.00	22.14 %	0.60	22.14 %	0.50	22.14 %	0.40	22.14 %	0.30
H Plant 1	-	1.36	1.00	1.36	0.70	1.36	0.60	1.36	0.50	1.36	0.50
H Plant 2	-	3.97	1.00	3.97	0.70	3.97	0.60	3.97	0.50	3.97	0.50
H Plant 3	-	7.55	1.00	7.55	0.70	7.55	0.60	7.55	0.50	7.55	0.50
H Plant 4	-	-	-	-	-	4.40	1.00	4.40	1.00	4.40	0.70

The energy demand *j* and the carbon emission limit factor of energy demand *j* at time *t* is shown in Table 3. As mentioned earlier, the energy demand values in Table 3 are estimated values based on Sarawak Energy's projection. The carbon emission limit factor must be reduced along the time periods to meet the carbon reduction target. However, it can be seen in Table 3 that the limit factor increases in the 2025 time period before reducing again in the following time periods. The increase is to account for the carbon emission from the two new combined-cycle blocks in NG plant. It is important to keep in mind that the carbon emission limit factors are hypothetical values that depict the carbon reduction target. The hypothetical values are values that can be adjusted based on the decision-maker's preference for the study.

Table 3: Table of energy demand j in MWh and carbon emission limit factor of energy demand j in tCO2eq/MWh at time t (in years).

Sarawak	Year (*t*)				
	2020	2025	2030	2035	2040
Energy Demand (MWh)	29,249,321	38,215,356	40,945,024	43,869,669	47,003,217
Emission Factor (tCO_2eq/MWh)	0.233	0.290	0.250	0.200	0.150

4. Results and discussion

The LP model was solved via AIMMS optimisation software version 4.78.2.4. The results obtained by solving the model in AIMMS for the source consumption of energy source *i* to produce electricity are tabulated in Table 4. From Table 4, it can be observed that by 2040, there is still a high amount of carbon-intensive sources being consumed to produce electricity in Sarawak. Even though the consumption of carbon-intensive sources in 2040 has reduced compared to the previous time periods, about 4,449,151 MWh of coal, 24,673,913 MWh of natural gas and 480,074 MWh of diesel are still required for electricity production. On the other hand, it can be noted that all the hydropower plants operate at maximum capacity in every time period. This is because of the hydropower plant's negligible net carbon emission. In order to meet the fixed carbon reduction limit, all the hydropower plants should be operating at maximum capacity. Moreover, the additional low carbon resources required to meet the energy demand is shown in Figure 1.

Table 4: Source consumption ($Scons_{i,t}$) of energy source i to produce electricity at time t (in years), (hydropower in m^3 & the rest of the i in MWh)

Energy Source (*i*)	Year (*t*)				
	2020	2025	2030	2035	2040
Coal	13,247,319	11,089,067	7,098,614	5,773,882	4,449,151
Natural Gas	10,825,040	32,591,670	24,524,832	30,188,580	24,673,913
Diesel	516,856	505,948	261,612	484,103	480,074
Hydropower	49,198,393,938	49,198,393,938	72,551,415,288	72,551,415,288	72,551,415,288

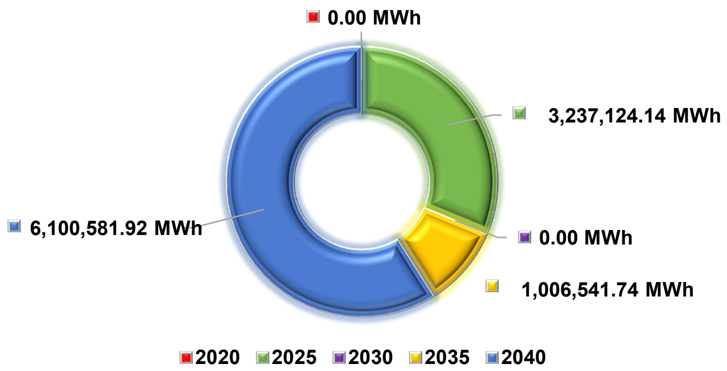

Figure 1: Additional low carbon resource required to meet the energy demand j at time t in MWh.

The values shown in Figure 1 are the additional low carbon resources required to meet the energy demand. This is needed when the existing carbon-intensive power plants reduce its source consumption, as seen in Table 4, which results in reduced electricity production to meet the carbon reduction limit. From Figure 1, no additional low carbon resources were required in 2020. This is because emissions in 2020 served as the base values for reduction limits in the subsequent years. This means that carbon reduction limits for 2025 were fixed based on 2020's emissions. In addition, no additional low carbon resources were also required in 2030 due to the commencement of a new hydropower plant in 2026. The new hydropower plant has sufficient capacity to meet the carbon reduction limit in that particular period. Moreover, the low carbon resources required in 2035 reduced compared to the value in 2025 due to the commencement of the new hydropower plant, which has negligible net carbon emission. As the time intervals proceed, the carbon reduction limit becomes stricter and more low carbon resources are required. This is seen in 2040 where the additional low carbon resource requirement has increased in amount. It is worth noting that the current study evaluates the minimum required low carbon resources to meet demands and carbon emission limits. The low carbon resources determined in each time period can be used as a basis for energy storage planning in future works. Energy storage planning can be introduced to the regional energy planning to reduce electricity losses while electricity is not needed or to compensate for insufficient electricity during peak hours.

5. Conclusion

In this study, a methodology was presented to optimise regional energy planning in order to meet electrical demands in a particular region. The presented methodology includes a mathematical optimisation model based on the carbon emission pinch analysis (CEPA) method that would assist in optimising the regional energy planning. The developed CEPA-based mathematical model allows a planner to plan a carbon-constrained energy system while meeting the energy demand requirements and the carbon reduction target. It also allocates low carbon energy sources to energy systems where it was required. The presented methodology was illustrated in an energy planning case study for the Sarawak region. From the case study, about 6,100,582 MWh of additional low carbon resources were required to meet the energy demand by 2040 in a carbon-constrained energy system. Energy storage planning can be incorporated in the future regional energy planning works with the additional low carbon resources as the basis.

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