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Optimal Regional Electricity Trading using P-Graph

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ABSTRACT

Many countries face the challenge of growing electricity demand, greenhouse gas emissions limits, and energy security goals. Decision support models can help plan energy systems to balance these considerations. In this paper, a P-graph optimisation model was developed to aid regional energy planning while considering current power generation capacity and potential growth. The model was demonstrated for two case studies: regional electricity trading in the Association of Southeast Asian Nations (ASEAN) and Canadian provinces. The Paris Agreement targets for 2030 were considered in both regions. For the ASEAN case, it was found that 289.33 TWh/y of renewable energy should be introduced to meet future demands. The change of allocation with cost and carbon emissions constraints was also analysed. For Canada, Alberta would need 36.02 TWh/y of additional hydropower or wind, or 41.16 TWh/y of additional solar energy. If nuclear energy were considered, at least 36.25 TWh/y would be needed.

KEYWORDS

Process graph, Energy planning, Electricity trading, Climate change mitigation, Renewable energy, Decarbonization.

INTRODUCTION

The 29th Conference of the Parties (COP29), held in November 2024, identified technical and governance options for deep decarbonization [1]. Despite commitments made in the 2015 Paris Agreement to reduce greenhouse gas (GHG) emissions, most countries continue to face challenges in meeting these targets due to rising energy demands [2]. Electricity generation is a significant contributor to global CO_2 emissions, accounting for approximately 40% of total emissions in 2022 [3]. Energy-related CO_2 emissions from electricity generation continue to rise, with an increase of 1.1% in 2023, reaching a new high of 37.4 Gt CO_2 [4]. These statistics show the importance of electricity generation and supply in reducing carbon emissions.

While replacing fossil energy sources with renewable energy (RE) is considered the ultimate approach for GHG emissions reduction, its deployment presents challenges related to cost, energy security, and public acceptance. The rapid increase in electricity demand in emerging economies further strains limited RE capacity. Electricity trading among neighbouring countries should be considered as a strategy to meet emissions reduction targets [5].

Current electricity trading systems, such as those in ISO New England and the Greater Mekong Subregion [6], are often unidirectional, which limits their efficiency and sustainability [7]. Transitioning to multidirectional trading, where energy can flow in various directions, could significantly enhance these systems' impact on emissions reduction and energy security. However, decision support tools will be needed to facilitate electricity trading.

Blockchain technology has emerged as a promising solution for optimising electricity trading within Carbon Management Networks (CMNs) by enhancing transparency [8], efficiency, and security [9]. While blockchain offers a novel method to improve transparency and flexibility in electricity trading through peer-to-peer (P2P) networks, the complexity of multidirectional trading networks requires more than just enhanced data management [10]. Effective optimisation of these systems requires a robust decision-making tool that can address uncertainties and variability while incorporating a realistic modelling approach that reflects the complexity of multi-region electricity networks.

Process integration-based methods have also been proposed to facilitate the planning of the decarbonization of electricity production. One established approach for handling such a CMN problem is arguably process integration methods, where overall power demand and CO_2 emissions reduction may be considered simultaneously. The earliest method, Carbon Emissions Pinch Analysis (CEPA), was developed by Tan and Foo [11], which later evolved into algebraic and mathematical models for improved accuracy and targeting later evolved into algebraic models for improved accuracy and targeting [12]. Further development also includes mathematical models, which were developed by Pekala et al. [13] for optimal energy planning under constraints like land use and carbon footprints, which was later extended for CO_2 capture and storage. More recently, the P-graph approach, introduced by Tan et al. [14] also offers a way to optimise CMNs by determining the minimum CO_2-neutral energy that meets both energy demand and GHG emissions limits. More recently, a CEPA variant was developed for optimising electricity trading, considering just average annual flows without short-term fluctuations [5].

The P-graph framework presents an alternative modelling approach for decarbonising industrial systems [15]. P-graph is a graph theory-based approach to solving process network synthesis (PNS) problems [16]; its component algorithms are also suitable for solving a broader class of analogous PNS-like problems [17]. P-graph emphasises the influence of network structure on system performance, and has a set of efficient component algorithms developed specifically to leverage information inherent in all PNS and PNS-like problems [18].

Many of the key applications of P-graph to PNS and PNS-like problems are surveyed in the review of Friedler et al. [17]. In the energy sector, the P-graph framework has also shown the ability to optimise different systems. Vance et al. [19] demonstrated the use of P-graph modelling in designing sustainable supply chain structures, achieving potential reductions in operating costs by up to 17% when integrating biomass into the energy supply chain, along with a decrease in environmental impact. Ji et al. [20] developed a multi-period P-graph energy model incorporating hydrogen and battery storage, achieving systems that were 21.5 % and 5.3 % cheaper than those without energy storage. Shi et al. [21] applied the P-graph to optimise fossil and renewable energy distribution in island communities. Some recent works on P-graph were reported for electricity trading. In the work of Xu et al. [22], a model based on P-graph was used to determine the optimal form of clean energy export from islands. In another recent work by Kong [23] P-graph was used to optimise multi-period energy trading. Unlike the previous work by Kong et al. [23], the approach developed here focuses on electricity trading between national or regional entities, rather than corporate entities; it also takes into account both sources and sinks, while the model by Xu et al. [22] focuses on the exporter's perspective.

This paper addresses the aforementioned research gap by developing a P-graph approach to optimise regional electricity trade. As in the CEPA-based work by Lopez et al. [5], the scope of the work considers only long-term (e.g., annual) average flows and does not consider dispatch to cope with short-term (e.g., hourly) fluctuations of supply and demand. Optimising such systems can maximise decarbonization while guiding capital investment decisions in renewable power generation and electricity transmission infrastructure. The rest of this paper is structured as follows. In the following section, the problem statement of the paper is discussed. Next, the mathematical model used in P-graph, the P-graph framework, together with the methodology, is highlighted. A literature example from Lopez et al. [5] is demonstrated next for the model. It was followed by two case studies involving regional power trading within ASEAN and within Canada. These examples demonstrate the versatility of the approach in handling scenarios involving multiple countries (case study 1) or multiple regions within a single country (case study 2). Lastly, the conclusion and prospects for future work are discussed.

PROBLEM STATEMENT

Trading electricity among neighbouring countries or regions can help meet electricity demands without the need for additional power plants [5]. This also allows for the export of low-carbon electricity, displacing capacity in countries with higher grid carbon intensity [24]. As a result, this approach not only meets future electricity needs but also reduces GHG emissions.

The formal problem statement is given as follows. Given:

- A system consisting of n countries or regions
- For each region, the source is the current capacity, and the sink is the future electricity demand
- Data for each current country or region: electricity generation, SK_i, average CO_2 intensity $C_{out,i}$, total CO_2 emissions from electricity generation
- Data for each country or region in the future: electricity generation, SK_j, average CO_2 intensity $C_{in,j}$, total CO_2 emissions from electricity generation

The main objective is to minimise the amount of low-carbon sources introduced into the system, which at the same time meets the country's future electricity demand, while reducing its carbon intensity. By doing so, the requirement of low-carbon sources for high-demand countries does not have to be increased urgently, but instead, rely on imports from countries with lower grid CO_2 intensity [5]. It should be emphasised that this work is limited to the analysis of annual average electricity flows and does not consider short-term dynamics in balancing supply and demand. This scope is essential for planning investments in transmission infrastructure, but not power grid operations. A superstructure representation of this problem is given in FIGURE 1.

METHODOLOGY

P-Graph Framework

In this work, the models are implemented using the software P-graph Studio [25] developed by the team at the University of Pannonia in Hungary. The P-graph framework uses a bipartite graph representation to deal with PNS [16] and PNS-like problems [17]. The P-graph framework is based on five axioms that provide a rigorous mathematical foundation for its component algorithms [15].

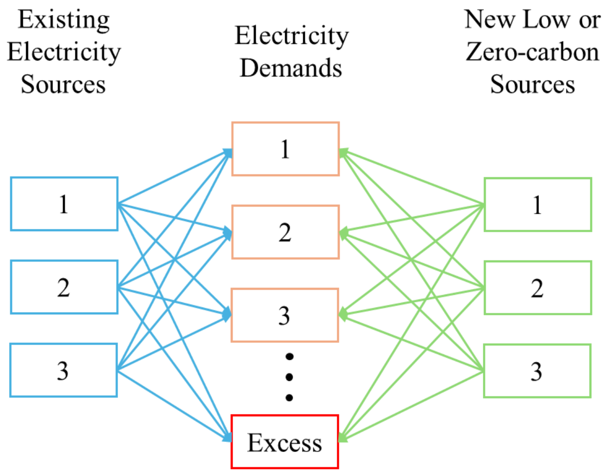

Figure 1. Superstructure representation for a two source two sink electricity trading system

In the traditional PNS context, materials are represented by M-type nodes and operations by O-type nodes in the P-graph framework. M-type nodes include raw materials (external inputs), products (exports), and intermediates (internal flows). Different types of nodes are shown in FIGURE 2.

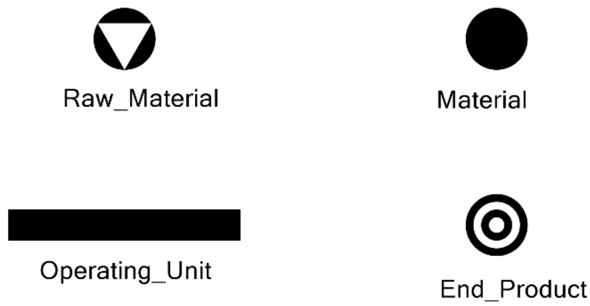

Figure 2. M-type and O-type representation

The framework has three component algorithms. First, Maximal Structure Generation (MSG), which generates the non-redundant union of all combinatorially feasible process structures of a PNS problem. The maximal structure is, in effect, a rigorously generated superstructure [26]. The Solution Structure Generation (SSG) algorithm generates all structurally feasible networks for the PNS problem [15]. Each solution structure is a candidate structure embedded in the maximal structure and can be the basis to identify a locally optimal network. Finally, the Accelerated Branch-and-Bound (ABB) algorithm generates the optimal solution structure from the set of structures generated by SSG, coupled with additional cost and flow information [27]. The ABB capitalises on information inherent in all PNS problems and is thus more computationally economical than conventional branch-and-bound techniques for generic mixed-integer programming problems. ABB identifies the optimal solution as well as local optima within the enumerated structures [15]. Such near-optimal solutions are often of great practical engineering value [17].

Any problem that can be mapped into an equivalent PNS problem can be solved with P-graph. For example, Tan et al. [14] showed that the source-sink matching problem often encountered in Process Integration can be expressed in PNS form, including the examples in [28] and [29]. Since it has previously been established that the electricity trading problem can be framed as a source-sink matching problem [5], it logically follows that it can also be solved with P-graph. This work also capitalizes on the PNS-like structure of regional electricity trading [28,29] as well as the flow of embodied GHG emissions. FIGURE 3 shows the CMN structure adopted from Tan et al. [14] for regional electricity trading in this work, where sources represent current capacity, and sinks represent future demand. This model is flexible enough and can be applied to any regions that share the same source-sink principle.

For the model in FIGURE 3, a CMN with one source (current capacity) and one sink (future demand) is shown. The energy source (represented by 'raw material' note) is linked to future demand and excess energy (both are 'product' note). Note that the future demand sink is also linked to an external carbon-neutral source ('raw material' note), which is used to determine the minimum future demand of renewable energy. Note that two 'product' notes are used to present fictitious load sinks that are not present in the actual process flow but refer to emission limits of future demand. The ratio of the ark is the CO_2 intensity of the source, which is used for calculating the CO_2 load between the sources and sinks. The allocation units ('operating units') between the sources and sinks are used for determining the amount of energy sources to be sent to the sinks.

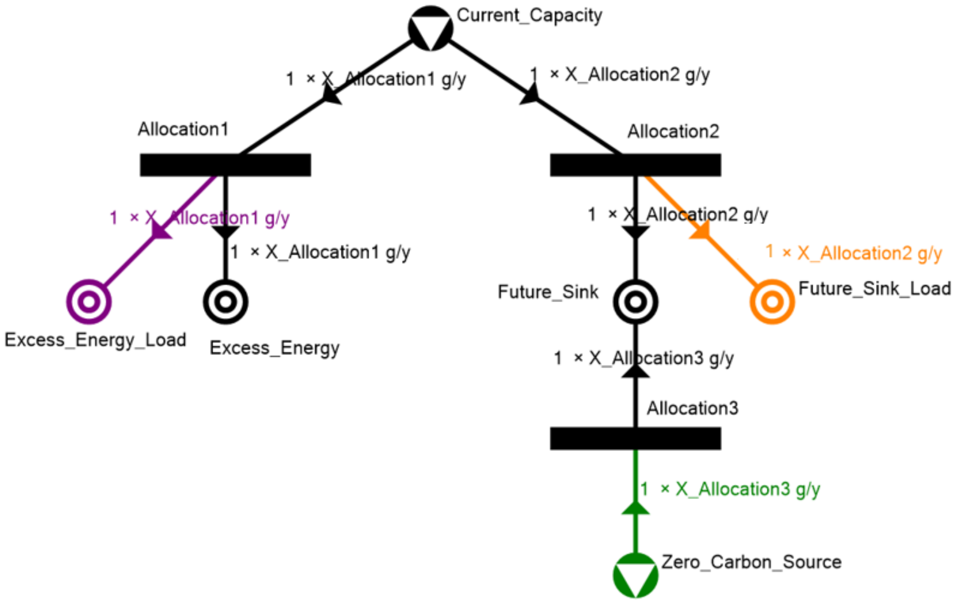

Figure 3. P-graph structure for the allocation of one source to one sink in a CMN

To determine the optimal allocation in the P-graph model, an arbitrary fictitious cost is set for carbon-neutral sources, while the cost for the current capacity is set to zero. This cost assignment allows P-graph to minimise the overall costs associated with electricity trading, identifying the most cost-effective solution.

The mathematical formulation involved in the P-graph model is presented in Appendix A-1. The objective function is to minimise the total amount of new renewable energy capacity to be shared by all countries in the system for electricity generation, at the same time allowing future increased demand for electricity with reduced CO_2 intensity to be met [30].

The following sections start with a literature example and continue with two additional case studies. Case Study 1 considers regional transmission between Malaysia to Indonesia, while Case Study 2 focuses on integrating different types of renewables into existing electricity trading systems in Canada.

Literature Example

TABLE 1 shows the data for a literature example taken from Tan et al. [30]. As shown, three countries have their current capacity (source) and future demand for energy, along with their current and future CO_2 intensity values. It is desired to identify the amount of additional amount of carbon-neutral electricity.

Table 1. Data for Literature Example [30]

Country	Current Capacity (TWh/y)	Current CO_2 intensity (Mt/TWh)	Current CO_2 emissions (Mt/y)	Future Demand (TWh/y)	Future CO_2 intensity limit (Mt/TWh)	Future CO_2 emissions limit (Mt/y)
1	60	0.40	24.00	75	0.24	18.00
2	40	0.70	28.00	40	0.35	14.00
3	20	0.90	18.00	25	0.81	20.25

TABLE 2 shows the solution generated by P-graph, with its superstructure shown in FIGURE 4. The carbon-neutral electricity generation was identified as 43.57 TWh/y (its total allocation to Countries 1 and 2), with 23.57 TWh/y of excess energy. Both values match the targets identified by CEPA in Tan et al. [30]. Note that P-graph has the ability to generate multiple near-sub-optimal solutions. For instance, TABLE 3 and TABLE 4 both display the same amount of carbon-neutral energy (45.71 TWh/y) and excess energy (25.71 TWh/y) as those in TABLE 2, but with different allocation patterns among the traded countries.

Table 2. Optimum Solution for Literature Example

Source	Sink			
	Country 1	Country 2	Country 3	Excess
Country 1	45	15	0	0
Country 2	0	11.43	25	3.57
Country 3	0	0	0	20
Carbon-neutral	30	13.57	0	0

Table 3. Near-optimum Solution 1 for Literature Example

Source	Sink			
	Country 1	Country 2	Country 3	Excess
Country 1	20	35	5	0
Country 2	14.29	0	0	25.71
Country 3	0	0	20	0
Carbon-neutral	40.71	5	0	0

Table 4. Near-optimum Solution 2 for Literature Example

Source	Sink			
	Country 1	Country 2	Country 3	Excess
Country 1	45	10	5	0
Country 2	0	14.29	0	25.71
Country 3	0	0	20	0
Carbon-neutral	30	15.71	0	0

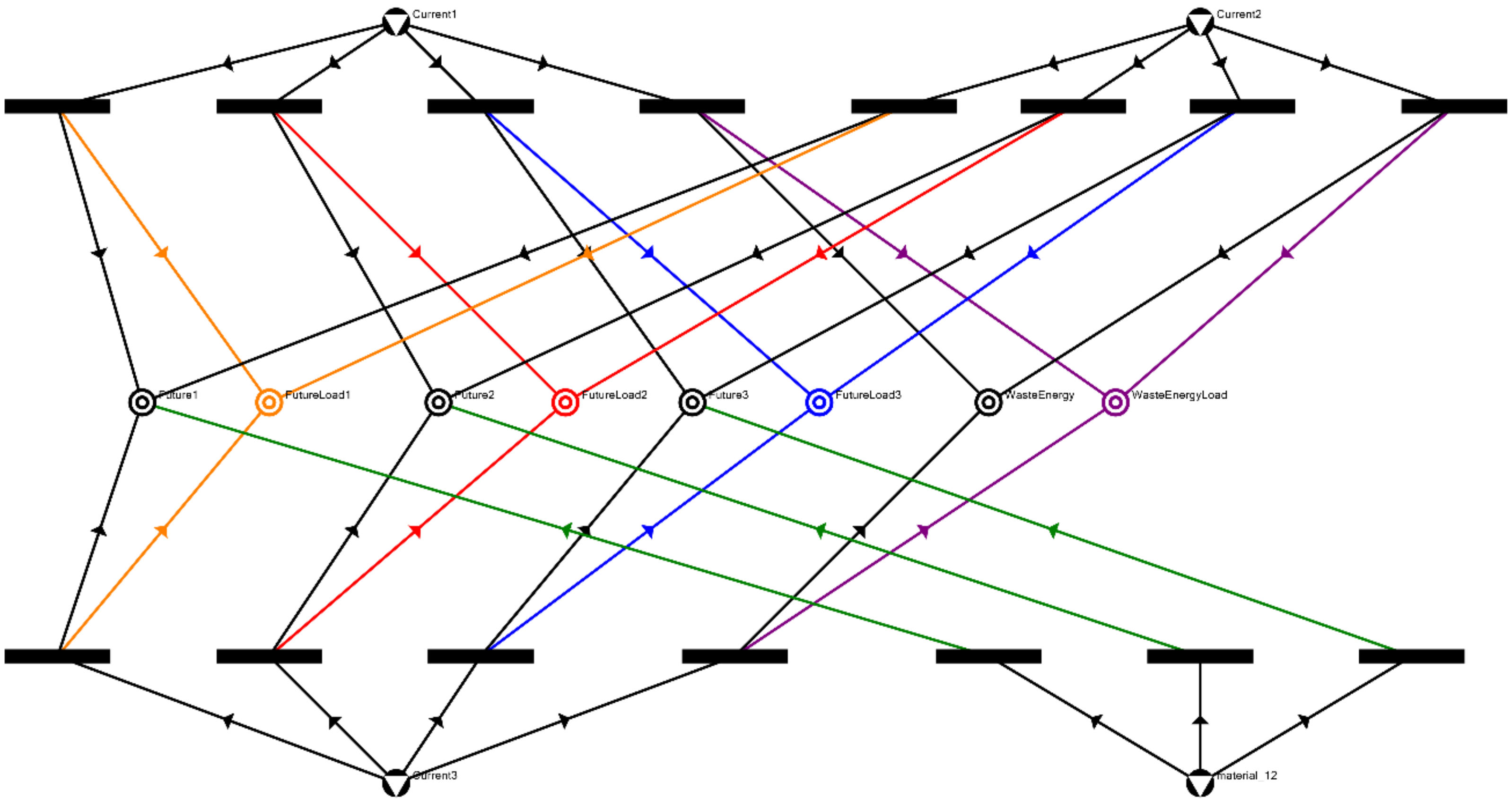

Figure 4. Maximal Structure for Literature Example

Case Study 1 – Brunei-Indonesia-Malaysia-Philippines East ASEAN Growth Area

Within the ASEAN community, several countries have engaged in power trading. One of the upcoming trading networks is the Brunei-Indonesia-Malaysia-Philippines East ASEAN Growth Area (BIMP-EAGA), suggested by the International Energy Agency (IEA) [7]. This case involves four countries, with data provided in TABLE 5. Currently, all countries are self-sufficient in electricity, with current capacity matching demand. Future emissions limits are based on commitments to the 2015 Paris Agreement, targeting 2030. While all countries are expected to increase electricity demand, their CO_2 intensity is set to decrease, except for Brunei, due to low-tariff electricity and overconsumption [31]. Emission reduction targets include Brunei's 30% reduction by 2030, Indonesia's 29% reduction from business-as-usual (BAU) emissions, Malaysia's 45% reduction in GHG intensity relative to GDP, and the Philippines' 70% reduction relative to a BAU scenario [32]. The countries aim to meet future demand by integrating renewable energy, assumed to have zero carbon intensity in this study.

Currently, there is only one regional transmission line within the area of study, which is from Sarawak (Malaysia) to Kalimantan (Indonesia). A few more interconnectors are proposed within Malaysia (connecting from Sarawak to Sabah), within Malaysia and nearby countries, i.e., Brunei and Sabah to Mindanao (Philippines), as shown in FIGURE 4 [7].

Table 5. Data for BIMP Case

Country	Current Capacity (TWh/y)	Current CO_2 intensity (Mt/TWh)	Current CO_2 emissions (Mt/y)	Future Demand (TWh/y)	Future CO_2 intensity limit (Mt/TWh)	Future CO_2 emissions limit (Mt/y)
Brunei Darussalam	3.8	0.811	3.08	2.79	0.941	2.63
Indonesia	263.3	0.865	227.78	337.26	0.592	199.59
Malaysia	157.2	0.715	112.36	211.90	0.335	70.98
Philippines	90.2	0.853	76.92	111.54	0.231	25.80

In the base case, renewables are assumed to be unlimited. The P-graph model results, shown in TABLE 6 and Appendix A-2, indicate that 289.33 TWh/y of renewable energy should be introduced, with an excess of 140.34 TWh/y from Indonesia, which can be converted into storage for emergency use in the future. This aligns with results obtained using CEPA [11]. Given Indonesia's high future demand, all countries must trade electricity with it to meet both CO_2 emission limits and future demand. Most renewables are allocated to Indonesia, Malaysia, and the Philippines, while none are sent to Brunei due to its decreasing demand; instead, Indonesia supplies 2.8 TWh/y to Brunei. The model does not consider specific renewable sources or transmission capacity limits, only current and future capacity constraints.

Table 6. Optimal Electricity Trade Matrix for Base Case (Units are in TWh/y)

Source	Sink				
	Brunei	Indonesia	Malaysia	Philippines	Excess
Brunei	0	3.8	0	0	0
Indonesia	2.79	120.17	0	0	140.34
Malaysia	0	21.85	99.27	36.08	0
Philippines	0	90.2	0	0	0
Renewables	0	101.24	112.63	75.46	0
Total	2.79	337.26	211.9	111.54	140.34

From the base case, 289.33 TWh/y of renewables are required for the system, making it important to identify their individual sources. The capacity of renewables from each country is analysed to ensure they can meet future demand. Table 7 summarises the source of the renewables from each country, taken from the International Renewable Energy Agency (IRENA). Future renewable capacities are estimated by extrapolating current trends in renewable energy supply for each country. However, this estimation may not represent the maximum potential capacity, as factors like long-term contracts, grid access, and new installations could increase future capacity [33]. Based on the data reported in IRENA, each country studied has at least one type of renewable energy, which ranges from solar energy, hydropower, biofuels, wind and geothermal [34].

Table 7. Future Estimation of Renewable Mix in Brunei, Indonesia, Malaysia and Philippines for 2030 (Units in TWh/y) [34]

Country	Solar	Hydropower	Biofuels	Geothermal	Wind	Total
Brunei	0.002	-	-	-	-	0.002
Indonesia	-	23.17	13.36	18.24	-	54.76
Malaysia	1.40	469.63	1.09	-	-	472.13
Philippines	5.57	7.83	2.85	11.94	3.12	31.31

The P-graph model was modified to reflect multiple projected renewable energy sources instead of one unlimited source, as in Figure 3. When renewable energy is supplied within its own country, transmission costs are lower due to the absence of wheeling charges—fees applied by transmission owners for transporting electricity over the grid.

In Scenario 1, as direct transmission lines are still not available among all countries, wheeling is required in order to allow power trading to occur. The wheeling charges are assumed to be 1 USD/TWh since there is no specific import or export price set under power purchase agreements (PPAs). In this scenario, wheeling charges are charged to electricity importers only. An assumption of no limits on transmission capacity for country-to-country transmission was made in this scenario.

The results of the model are shown in Table 8 and Table 9 (the P-graph maximal structure is shown in Appendix A-4). As shown, the main trading occurs between Malaysia, Indonesia, and the Philippines. This is due to the lesser demand of Brunei, making it less involved in direct trading. Its role is more on wheeling electricity to and from the Philippines, Malaysia, and Indonesia.

Table 8. Optimal Electricity Trade Matrix for Scenario 1 (Units are in TWh/y)

Source	Sink				
	Brunei	Indonesia	Malaysia	Philippines	Excess
Brunei	0	3.8	0	0	0
Indonesia	2.79	120.17	0	0	140.34
Malaysia	0	115.61	5.51	36.08	0
Philippines	0	11.60	78.60	0	0
Renewables	0	86.07	127.80	75.46	0

In comparison of the results of Base Case and Scenario 1, the majority of the distributions are similar, with only a few differences spotted, evidently in the trading among Indonesia, Malaysia, Philippines, and the number of renewables allocated to each country. One of the main differences is that Malaysia's electricity from current capacity to future demand decreased as it relied more on its own renewables (see **Table 7**), increasing from 112.63 TWh/y to 127.80 TWh/y (see **Table 6** and **Table 8**). This shift reduced Malaysia's dependence on "dirty" energy from 99.27 TWh/y to 84.11 TWh/y.

As for Indonesia, the imported renewable energy reduced from 101.24 TWh/y (**Table 6**) to 86.07 TWh/y (**Table 8**). However, with the knowledge of renewable energy sources and the assumption that energy transmitted to their own country will have a lesser cost compared to country-to-country transmission, the renewables from Indonesia will be supplied to them first. With the decrease in renewable energy distributed to them, more electricity is required to be exported to them in order to fulfil their future demand. This is reflected in the increment of electricity imported from Malaysia, which is from 21.85 TWh/y to 115.61 TWh/y to meet future demand due to Malaysia's less carbon-intensive energy mix.

Table 9. Breakdown of Total Renewable Sources to Sinks (289.33 TWh/y) in Scenario 1

Source	Sink			
	Brunei	Indonesia	Malaysia	Philippines
Brunei	-	-	-	-
Solar	-	-	-	-
Indonesia	-	54.76	-	-
Biofuel	-	13.36	-	-
Hydropower	-	23.17	-	-
Geothermal	-	18.24	-	-
Malaysia	-	-	127.80	75.46
Solar	-	-	-	-
Hydropower	-	-	127.80	75.46
Biofuel	-	-	-	-
Philippines	-	31.31	-	-
Solar	-	5.57	-	-
Hydropower	-	7.83	-	-
Biofuel	-	2.85	-	-
Geothermal	-	11.94	-	-
Wind	-	3.12	-	-

Another observation found was that both the renewables for Indonesia and the Philippines are depleted to fulfil their own future demands, as there will be no wheeling charges if it is self-supplied. Also, renewables for Brunei are untouched, as the total amount of renewable generation is relatively negligible compared to its future demand. Thus, on an economic scale, it is not worth it if Brunei's renewables were to be included in the trading matrix. This may not be the most optimal distribution as this may deplete the renewable potentials of said countries, which will make their commitments to the regional electricity trading system more difficult to fulfil in the long run, as it will limit their own development. To make this work, a strong and robust management of the system has to be in place so as not to put any particular country at a disadvantage.

In the development of renewable energy generation, a common barrier found was transmission system constraints. Unlike conventional power sources, renewables like solar, hydro, and wind must be generated at specific locations. These sites are often far from population centres with high electricity demand, which necessitates greater investment in transmission infrastructure [35].

Hence, Scenario 2 presents an improvised version of Scenario 1, which costs for country-to-country transmission will also include source-to-grid costs, borne by the importer. Similar to Scenario 1, it is assumed that source-to-grid costs are assumed to be constant for all sources, with an arbitrary value of 1 USD/TWh for fixed operational cost in this scenario. The results generated by P-graph are shown in TABLE 10 and TABLE 11, and the P-graph results are shown in the appendix. The total amount of both renewables' excess energy remains identical to the previous scenario, i.e. 140.34 TWh/y and 289.33 TWh/y, respectively.

Table 10. Optimal Electricity Trade Matrix for Scenario 2 (Units are in TWh/y)

Source	Sink				
	Brunei	Indonesia	Malaysia	Philippines	Excess
Brunei	0	0	0	3.8	0
Indonesia	2.79	120.17	0	0	140.34
Malaysia	0	133.76	23.44	0	0
Philippines	0	0	63.57	26.63	0
Renewables	0	83.32	124.90	75.46	0

Table 11. Breakdown of 289.33 TWh/y of Renewable Sources to Sink for Scenario 2

Source	Sink			
	Brunei	Indonesia	Malaysia	Philippines
Malaysia	-	83.32	124.90	81.11
Solar	-	-	-	-
Hydropower	-	83.32	127.80	75.46
Biofuel	-	-	-	-

Comparing Scenarios 1 and 2, one of the main differences observed is in terms of the export of Brunei. In the earlier scenario, Brunei have been exporting its electricity to Indonesia, whereas in Scenario 2, Brunei exports to the Philippines instead. Another difference seen is how the Philippines does not supply electricity to itself in the earlier scenarios, but they now self-supply 26.63 TWh/y of electricity in Scenario 2. In this scenario, the interconnector of 3.8 TWh/y exported to Philippines from Brunei is beneficial to the entire system as electricity trading between Malaysia and Philippines can be wheeled through Brunei, wherein in the scenario of the Base Case and Scenario 1, an additional interconnector must be built between Brunei and Philippines with no net transmission between them for trading between Philippines, Indonesia, and Malaysia.

Lastly, from TABLE 11, it is observed that only one source of renewable energy is being introduced, i.e. hydropower from Malaysia, due to the introduction of transmission cost and wheeling charges in this scenario. As the total amount of renewables, as calculated previously, is 289.33 TWh/y and the total amount of hydropower from Malaysia is 469.63 TWh/y, this source can supplement the network's needs. Aside from that, instead of depleting the renewable sources from Indonesia and the Philippines as suggested in Scenario 1, there will be a surplus in renewable energy supply for all sources with this selection of distribution. Also, by having two sources of renewables, an investment of a higher capital cost for electricity transmission infrastructure is required. Hence, to be able to cut costs at the same time fulfil the network's requirement, hydropower from Malaysia is the main and only renewable source chosen in this scenario.

Case Study 2 – Canadian Provinces (Alberta, British Columbia)

Alberta, along with other Canadian provinces, engages in inter-provincial electricity trade. While Alberta and Ontario have deregulated wholesale electricity markets, Alberta stands out with the highest refining capacity [36]. Alberta imports and exports electricity primarily with British Columbia, Saskatchewan, and Montana [37]. According to Alberta Electric System Operator's (AESO) [38], the province's electricity capacity in 2030 is projected to shift towards renewables and away from coal (TABLE 12). Natural gas will remain the dominant non-renewable source, supplemented by hydropower, wind, and solar. All cogeneration, combined cycle, simple cycle, and coal-to-gas facilities will use natural gas. The projected electricity capacity for Alberta in 2030 is detailed in TABLE 12.

Table 12. Alberta's forecasted electricity capacity by fuel, in 2030 [38]

Fuel	Coal-fired	Cogene-ration	Combined cycle	Simple cycle	Coal-to-gas	Hydro-power	Wind	Solar	Other	Total
Capacity (MW)	0	5,499	2,227	1,835	4,890	894	3854	231	423	19,853

TABLE 13 presents the maximum electricity generation data by source for Alberta in 2030, calculated assuming 8,760 h/y of operation. Capacity factors from 2015 to 2019 [37], [39], [40], [41], [42] were estimated by comparing the actual electricity generation to the maximum electricity generated at full capacity, based on data from the Alberta Utilities Commission (AUC). The mean capacity factor for each resource was calculated from these five years. An exception is made for solar, which was minimally utilised until 2018. Thus, only 2018 [37] and 2019 [40] data are considered for it. The actual maximum electricity is obtained by multiplying the maximum electricity generated at full capacity by the capacity factor.

Table 13. Maximum electricity generation data in Alberta by source in 2030

Source	Natural Gas	Hydropower	Wind	Solar
Maximum electricity generated at full capacity (GWh/y)	126,590.76	7,831.44	33,761.04	2,023.56
Capacity factor (%)	59.65	23.42	31.61	16.25
Actual maximum electricity generation (GWh/y)	75,510.57	1,834.47	10,673.04	328.79

Alberta's electricity demand in 2030 is assumed to be the peak demand in AESO's reference case in its published Long-term Outlook in 2019 [38]. Alberta aims for a maximum of 209 Mt-CO_2-e in total GHG emissions by 2030 under the Paris scenario [43], with electricity generation expected to account for 16% of this total [44]. The main targets of the P-graph model are shown in TABLE 14.

Table 14. Main targets of the P-graph model for Alberta in 2030

Alberta's electricity demand (GWh/y)	116,674.44
Electricity generation emissions limit (Mt CO_2-e)	33.44

The demand of Alberta's trading partners in 2030 was estimated based on expected changes in their electricity generation capacity. By 2030, electricity generation is expected to increase by 50% in British Columbia [45] and by 55.6% in Saskatchewan compared to 2018 [46]. For Montana, a 10% increase from 2019 power demand based on the increment of the demand in North America in the same period is assumed [47]. Alberta's exports to these regions in 2018 and 2019 are scaled accordingly to estimate their 2030 demand.

Emission limits regions are estimated based on Alberta's targeted emission intensity of 286.61 t/GWh by 2030 (= 33.44 x 1,000,000 / 116,674.44 t/GWh; see TABLE 14). For Alberta's import potential, the maximum annual electricity imports from each trading partner from 2011 to 2019 were identified using data from AUC.

TABLE 15 shows the electricity trading data of Alberta by 2030. TABLE 16 lists the carbon intensity values for each fuel source, based on their lifecycle GHG emissions from the World Nuclear Association [48]. The average carbon intensities of Alberta's trading partners are assumed to remain constant, as shown in TABLE 17.

Table 15. Electricity trading data of Alberta by 2030

Province/State	Electricity demanded from Alberta (GWh/y)	Emissions limit of electricity demanded from Alberta (t-CO_2-e)	Maximum potential exported electricity to Alberta (GWh/y)
British Columbia	813.15	233,056.49	3,321.10
Saskatchewan	225.40	64,601.78	545.20
Montana	47.96	13,745.79	957.80

Table 16. Carbon intensity by fuel type [48]

Fuel Type	Natural Gas	Hydropower	Wind	Solar
Carbon intensity (t CO_2-e/GWh)	499	26	26	85

Table 17. Carbon intensity values for Alberta trading partners

Province/State	British Columbia	Saskatchewan	Montana
Carbon Intensity (t CO_2-e/GWh)	18.9 [49]	660 [49]	160 [50]

In Scenario 1, the addition of more hydropower or wind capacity to the power mix of Alberta is studied. The GHG intensity of the additional renewable resource is set at 26 t CO_2-e/GWh which is the same as that of hydropower or wind. More than 500 optimal and near-optimal solutions were obtained. FIGURE 5 presents the maximal structure for the case study. TABLE 18 shows the electricity generation of Alberta with three selected feasible solutions. TABLE 19, TABLE 20 and Table 21 show the exports of Alberta by resource for these solutions. Optimal solution results show that the minimum additional hydropower or wind required in the system is equal to 36,023.20 GWh/y, while sub-optimal solution has slightly higher value.

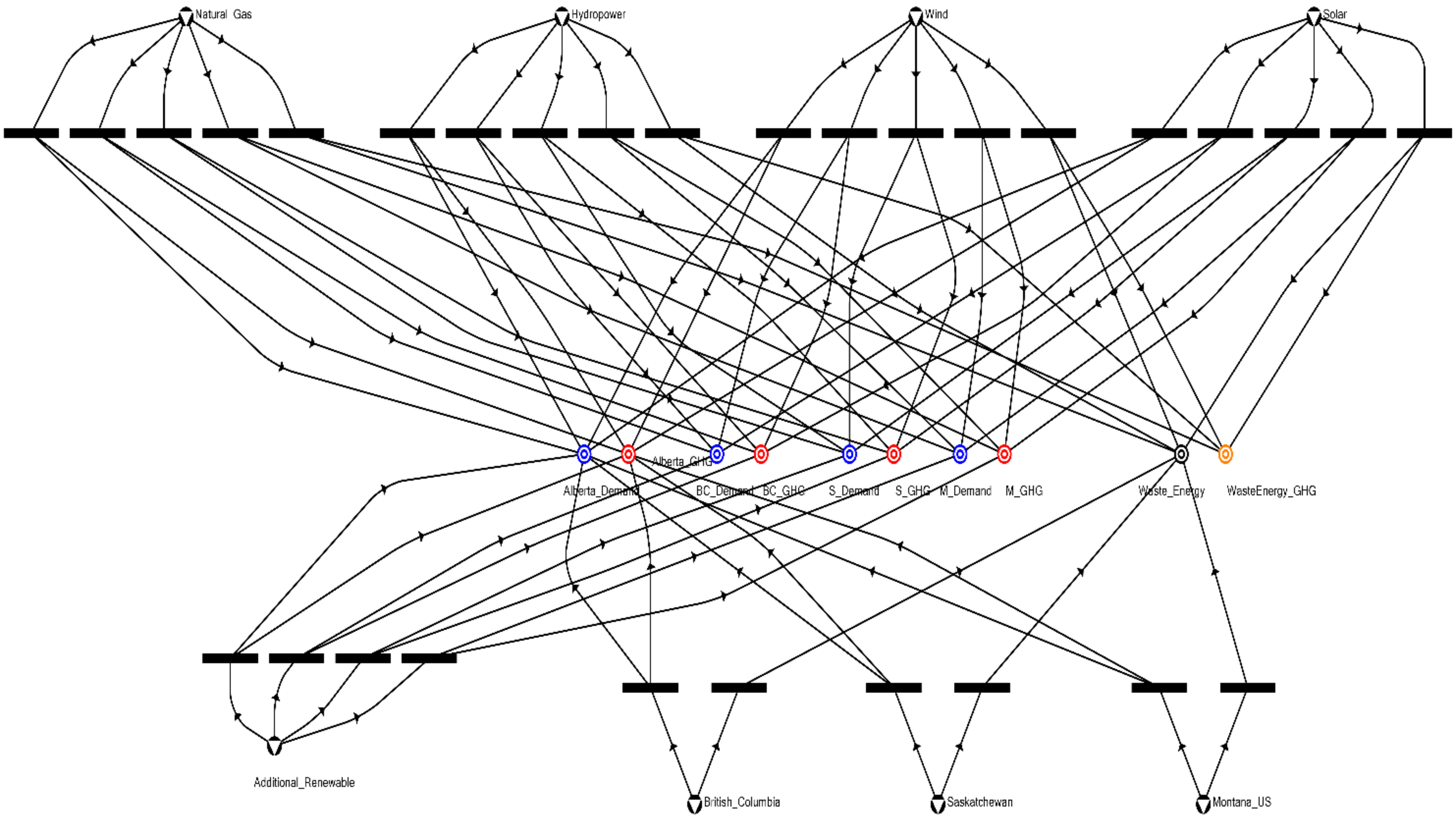

Figure 5. Canadian Provinces Case Study - Maximal Structure

Table 18. Scenario 1 - Alberta's electricity generation by source for three feasible solutions

	Electricity generated by source (GWh/y)							
Solution	Natural Gas	Hydro-power	Wind	Solar	Additional Renewable Resource	Imports - British Columbia	Imports - Saskat -chewan	Imports - Montana
Feasible Solution 1 - Optimal	64,064.90	1,634.37	10,673	0	36,023.20	3,321.10	0	957.80
Feasible Solution 2 - Optimal	64,027	1,733.26	10,307.9	304.19	36,023.20	3321.10	0	957.80
Feasible Solution 3 - sub-optimum	64,064.90	1,834.47	10,350.4	0	36,145.7	3,321.10	0	957.80

Table 19. Scenario 1 – Feasible Solution 1 – Alberta's exports by resource (GWh/y) – optimal

Province/State	Source				
	Natural Gas	Hydropower	Wind	Solar	Additional Renewable Resource
British Columbia	407.01	77.35	0	328.79	0
Saskatchewan	124.19	101.21	0	0	0
Montana	26.42	21.54	0	0	0

Table 20. Scenario 1 – Feasible Solution 2 – Alberta's exports by resource (GWh/y) – optimal

Province/State	Source				
	Natural Gas	Hydropower	Wind	Solar	Additional Renewable Resource
British Columbia	448.02	0	365.13	0	0
Saskatchewan	124.19	101.21	0	0	0
Montana	23.36	0	0	24.60	0

Table 21. Scenario 1 – Feasible Solution 3 – Alberta's exports by resource (GWh/y) – sub-optimal solution

Province/State	Source				
	Natural Gas	Hydropower	Wind	Solar	Additional Renewable Resource
British Columbia	435.13	0	274.63	103.39	0
Saskatchewan	0	0	0	225.4	0
Montana	0	0	47.96	0	0

Scenario 2 focuses on the increased solar capacity in Alberta. The intensity of the additional resource is adjusted to 85 t CO_2-e/GWh, which is equivalent to that of solar. TABLE 22 shows the electricity generation of Alberta by source with respect to three different feasible solutions. TABLE 23, TABLE 24 and TABLE 25 show the exports of Alberta by resource for these solutions. The minimum required amount of additional renewable electricity of solar is 41,157 GWh/y, while the sub-optimal solution has slightly higher value of 41,180 GWh/y.

Table 22. Scenario 2 - Alberta's electricity generation by source for three feasible solutions

Solution	Electricity generated by source (GWh/y)							
	Natural Gas	Hydro-power	Wind	Solar	Additional Renewable Resource	Imports - British Columbia	Imports -Saskat-chewan	Imports - Montana
Feasible Solution 1 - Optimal	55,890.10	1,368.13	10,651.5	328.79	41,157	3,321.10	0	957.80
Feasible Solution 2 - Optimal	58,890.10	1,469.34	10,550.3	328.79	41,157	3,321.10	0	957.80
Feasible Solution 3 - sub-optimum	58,928.20	1,834.47	10,452.5	0	41,180	3,321.10	0	957.80

Table 23. Scenario 2 – Feasible Solution 1 – Alberta's exports by resource (values in GWh/y) – optimal solution

Province/State	Source				
	Natural Gas	Hydropower	Wind	Solar	Additional Renewable Resource
British Columbia	448.02	365.13	0	0	0
Saskatchewan	124.19	101.21	0	0	0
Montana	26.42	0	21.54	0	0

Table 24. Scenario 2 – Feasible Solution 2 – Alberta's exports by resource (values in GWh/y) – optimal solution

Province/State	Source				
	Natural Gas	Hydropower	Wind	Solar	Additional Renewable Resource
British Columbia	448.02	365.13	0	0	0
Saskatchewan	124.19	0	101.21	0	0
Montana	26.42	0	21.54	0	0

Table 25. Scenario 2 – Feasible Solution 3 – Alberta's exports by resource (values in GWh/y) – sub-optimal solution

Province/State	Source				
	Natural Gas	Hydropower	Wind	Solar	Additional Renewable Resource
British Columbia	427.42	0	220.54	165.20	0
Saskatchewan	109.77	0		115.64	0
Montana	0	0		47.96	0

Lastly, Scenario 3 evaluates the need for nuclear power to meet the model's targets if Alberta decides to incorporate nuclear technology into its power generation. This is considered in the P-graph model by adjusting the GHG intensity of the additional resource to be 29 t- CO_2-e/GWh, equivalent to that of nuclear power generation. TABLE 26 shows the electricity generation of Alberta by source with respect to three different feasible solutions. TABLE 27, TABLE 28 and TABLE 29 show the exports of Alberta by resource for these solutions. To meet the model's targets, a minimum of 36,253.20 GWh/y of electricity from nuclear resources is required, while the sub-optimal solution has higher value of 36,467.50 GWh/y.

Table 26. Scenario 3 - Alberta's electricity generation by source for three feasible solutions

	Electricity generated by source (GWh/y)							
Solution	Natural Gas	Hydropower	Wind	Solar	Additional Renewable Resource	Imports - British Columbia	Imports - Saskatchewan	Imports - Montana
Feasible Solution 1 - Optimal	63,808.40	1,447.81	10,673	213.16	36,253.20	3,321.10	0	957.80
Feasible Solution 2 - Optimal	63,835.00	1,834.47	10,472.9	0	36,253.20	3,321.10	0	957.80
Feasible Solution 3 - sub-optimial	63,833.60	1421.38	10,673	0	36,467.50	3,321.10	0	957.80

Table 27. Scenario 3 – Feasible Solution 1 – Alberta's exports by resource (values in GWh/y) – optimal solution

Province/State	Source				
	Natural Gas	Hydropower	Wind	Solar	Additional Renewable Resource
British Columbia	448.02	365.13	0	0	0
Saskatchewan	109.77	0	0	115.64	0
Montana	26.42	21.54	0	0	0

Table 28. Scenario 3 – Feasible Solution 2 – Alberta's exports by resource (values in GWh/y) – optimal solution

Province/State	Source				
	Natural Gas	Hydropower	Wind	Solar	Additional Renewable Resource
British Columbia	410.08	0	98.88	304.19	0
Saskatchewan	124.19	0	101.21	0	0
Montana	23.36	0	0	24.60	0

Table 29. Scenario 3 – Feasible Solution 3 – Alberta's exports by resource (values in GWh/y) – sub-optimal solution

Province/State	Source				
	Natural Gas	Hydropower	Wind	Solar	Additional Renewable Resource
British Columbia	448.02	365.13	0	0	0
Saskatchewan	0	0	0	225.40	0
Montana	0	47.96	0	0	0

The case study data in TABLE 13 shows that Alberta's total maximum electricity generation capacity in 2030 is projected to be 88,346.87 GWh/y (sum of all entries in the last row), falling short of the required 116,674.44 GWh/y (see TABLE 14). Therefore, additional capacity or increased imports are essential, regardless of GHG emission limits. The solutions obtained for the scenarios had some commonality. It is noticed that natural gas is the only resource not utilised fully, due to its high GHG intensity, and being the only non-renewable resource. Imports from Saskatchewan are avoided due to its high GHG intensity of 660 t CO_2-e/GWh, while British Columbia and Montana are prioritised for their lower intensities. To meet the 2030 demand and emission targets, Alberta would need an additional 36,023.20 GWh/y from hydropower or wind, or 41,157 GWh/y from solar. This equates to adding about 13,009 MW of wind, 17,559 MW of hydropower, or 28,913 MW of solar capacity.

Given Alberta's forecasted capacity of 4,979 MW from these renewables by 2030, such additions seem impractical due to their low-capacity factors and intermittent nature [51]. Hydropower depends on water availability, wind power on wind speeds, and solar power on daylight, with Alberta's lower sunlight levels further reducing solar capacity factors [43].

Nuclear energy presents a more feasible option. Alberta would need a minimum of 36,253.17 GWh/y to reach the targets of the model. With a global mean capacity factor of 82.5% [48], Alberta would require approximately 5,016 MW of nuclear capacity. Alberta has significant nuclear potential, notably with the Athabasca basin's uranium reserves [52]. However, traditional large nuclear units face challenges due to the need for substantial reserve capacity and transmission upgrades [53].

In April 2021, Alberta signed the Memorandum of Understanding joining three other provinces in an agreement to support the development of Small Modular Reactors (SMRs) as a source of clean energy [54]. SMRs are nuclear reactors that produce a maximum of 300 MW of electricity, and according to the Memorandum of Understanding, have the potential to improve the safety, economic and environmental advantages of nuclear energy [55]. SMRs could be key in helping Alberta achieve its electricity demand and emission targets should the province decide to pursue the technology in the future.

CONCLUSION

In this paper, a novel method for optimising regional electricity trade was developed based on the P-graph framework. Its main contribution is the capability to compute electricity trading schemes to balance energy demand, resource allocation, and emission reduction targets across regions. Two case studies were used to illustrate its applications, i.e. the BIMP-EAGA in ASEAN and Canadian provinces. The case studies clearly illustrate the potential of optimising regional electricity trade as a carbon management strategy. The amount of additional renewable capacity required can be minimised with electricity trading among regions. Regional electricity trade allows regions to meet their energy demands while minimising additional renewable capacity requirements. For instance, to meet both CO_2 emission limits and the future energy demand of BIMP-EAGA, it is necessary to introduce 289.33 TWh/y of renewables, predominantly using hydropower (from Malaysia), while an excess of fossil fuel generation of 140.34 TWh/y (from Indonesia) is observed. In the Canadian context, Alberta could meet its 2030 targets with several options, either an additional 36.02 TWh/y from hydropower/wind (scenario 1), 41.16 TWh/y from solar (scenario 2), or 36.25 TWh/y from nuclear (scenario 3). This has relevance not only for the specific regions studied but also for policymakers and stakeholders globally who aim to balance energy security, economic efficiency, and climate goals.

Future studies can be extended on this work by including considerations of electricity markets and the carbon trading schemes. In addition, more aspects such as geographical constraints, transmission limit constraints can be included to further study the feasibility of the allocation. Practical policy implications should also be considered. Multi-period models considering the short- and long-term dynamics of electricity trading can also be developed.

NOMENCLATURE

Abbreviations

ABB	Accelerated Branch-and-Bound
AESO	Alberta Electric System Operator's
AUC	Alberta Utilities Commission
BAU	Business-as-Usual
BIMP	Brunei-Indonesia-Malaysia-Philippines
CEPA	Carbon Emissions Pinch Analysis
CMN	Carbon Management Network
COP27	27th Conference of Parties
CO_2	Carbon Dioxide
EAGA	East ASEAN Growth Area
GHG	Greenhouse Gas
IRENA	International Renewable Energy Agency
MSG	Maximal Structure Generation
PNS	Process Network Synthesis
P2P	Peer-to-Peer
RE	Renewable Energy
SMR	Small Modular Reactor
SSG	Solution Structure Generation

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APPENDIX

A1. Mathematical Programming Model

The problem revolves around determining the amount of electricity capacity each country has, which can be further traded to meet unique demands for different countries in the future. The mathematical formulation, as follows, is applicable to the power trading problem:

Subscripts

i	Index for current electricity capacity
j	Index for future electricity capacity

Parameters

$C_{out,i}$	Current CO_2 emission factor of current electricity capacity, i
$C_{in,j}$	Future CO_2 emissions limit of future electricity capacity, j
SR_i	Quantity of current electricity capacity, i
SK_j	Quantity of future electricity capacity, j

Decision Variable

Z_j	Renewable energy will be supplied to future electricity capacity
W_i	Unused portion of current electricity capacity, i
$F_{i,j}$	Electricity supplied from current electricity capacity i to future electricity capacity, j

The objective function is to minimise the total amount of new renewable energy capacity to be shared by all countries in the system for electricity generation, at the same time allowing future increased demand for electricity with reduced CO_2 intensity to be met [5]:

Min Z_j

The problem is subject to a few constraints. Energy balance for each current electricity capacity:

$$W_i + \sum_j F_{i,j} = SR_i \quad \forall i \tag{1}$$

Energy balance for each future electricity capacity

$$Z_j + \sum_i F_{i,j} = SK_j \tag{2}$$

The emission limits, a product of SK_j and C_{in} of each future electricity capacity, must be met by the energy mix supplied to it.

$$\sum_i C_{out,i}\, F_{i,j} \le SK_j C_{in,j} \quad \forall j \tag{3}$$

All variables in the system must be non-negative.

$$Z_j, W_i, F_{i,j} \ge 0 \quad \forall\, i,j \tag{4}$$

A2. Solution Structure for Example Case

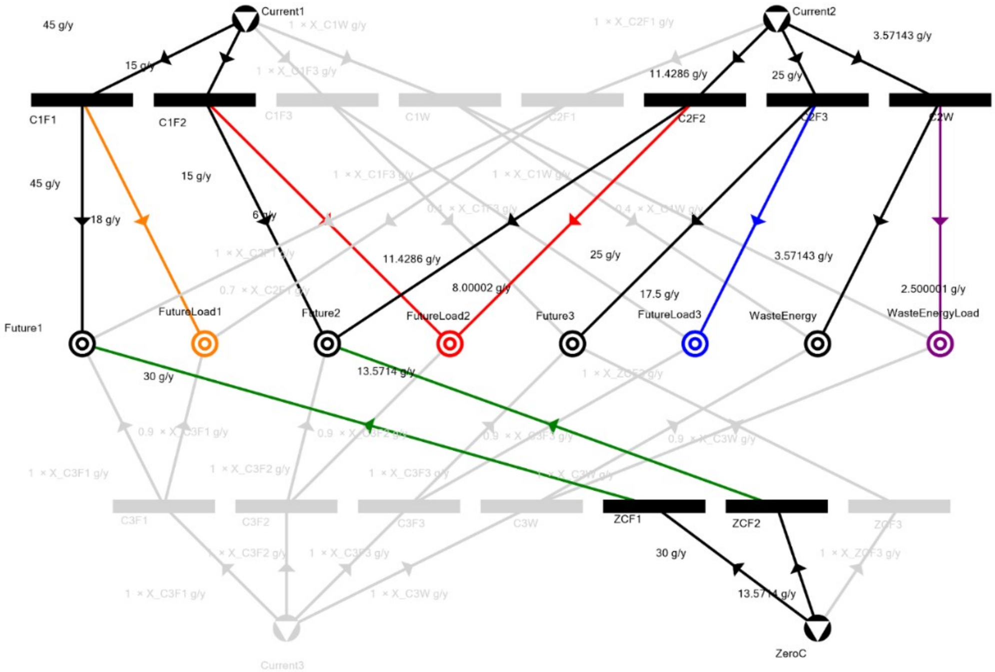

Figure A1. Feasible Solution 1 for Example Case

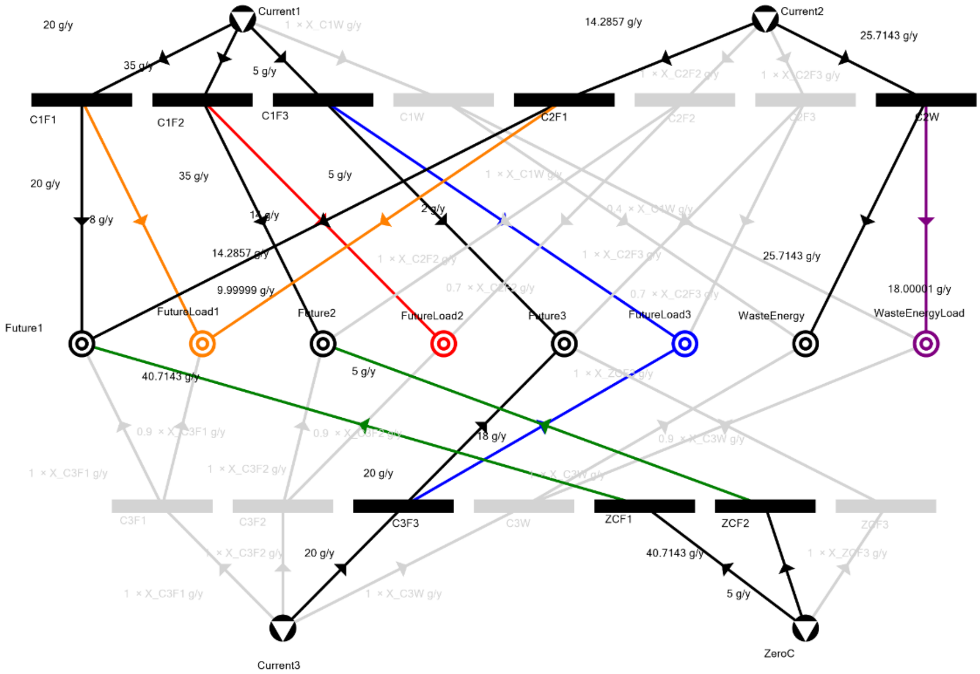

Figure A2. Feasible Solution 2 for Example Case

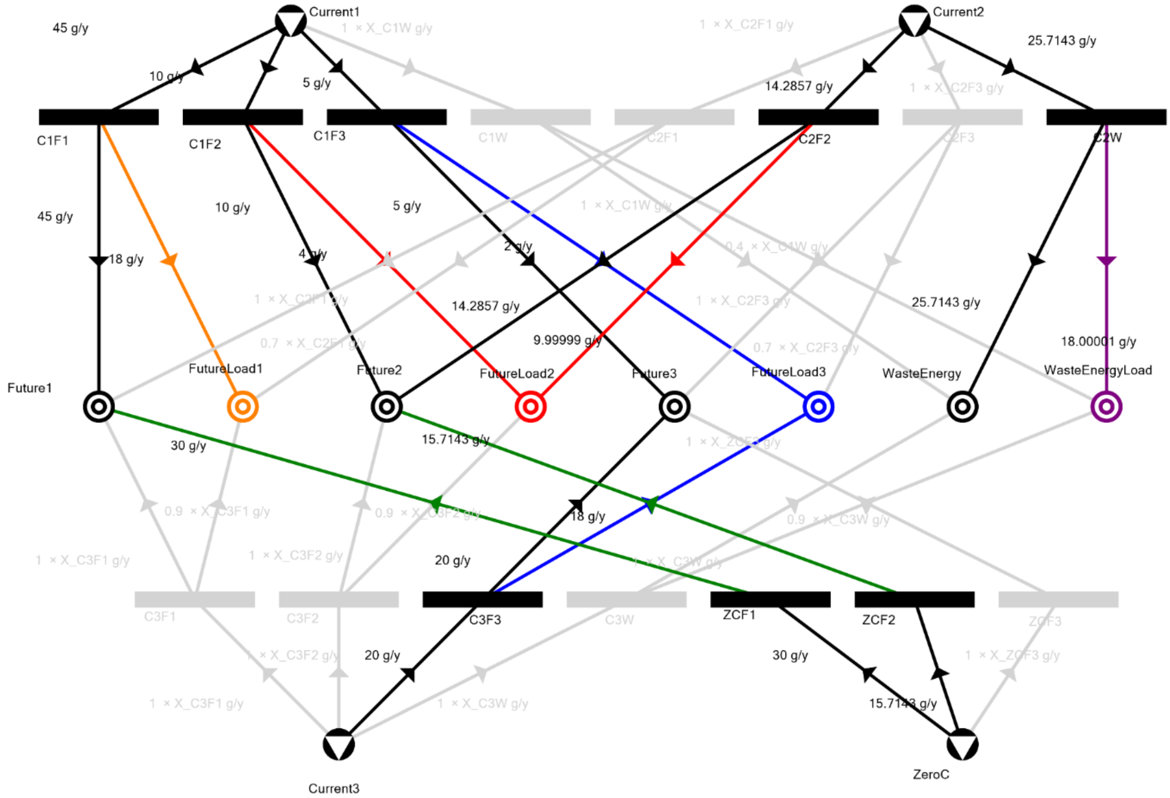

Figure A3. Feasible Solution 3 for Example Case

A3. Calculation for Estimation of Future Renewables

A set of data was given by Cho and Moon [34]:

Table A1: Renewable Energy Installed Capacity in Brunei

Brunei (Year)	Solar (GWh)
2010	0.81
2011	1.624
2012	1.667
2013	1.692
2014	1.6
2015	1.293
2016	1.067
2017	1.545
2018	1.596

To estimate the future renewable capacity in Brunei (Year 2030), a graph was plotted as shown in FIGURE A4:

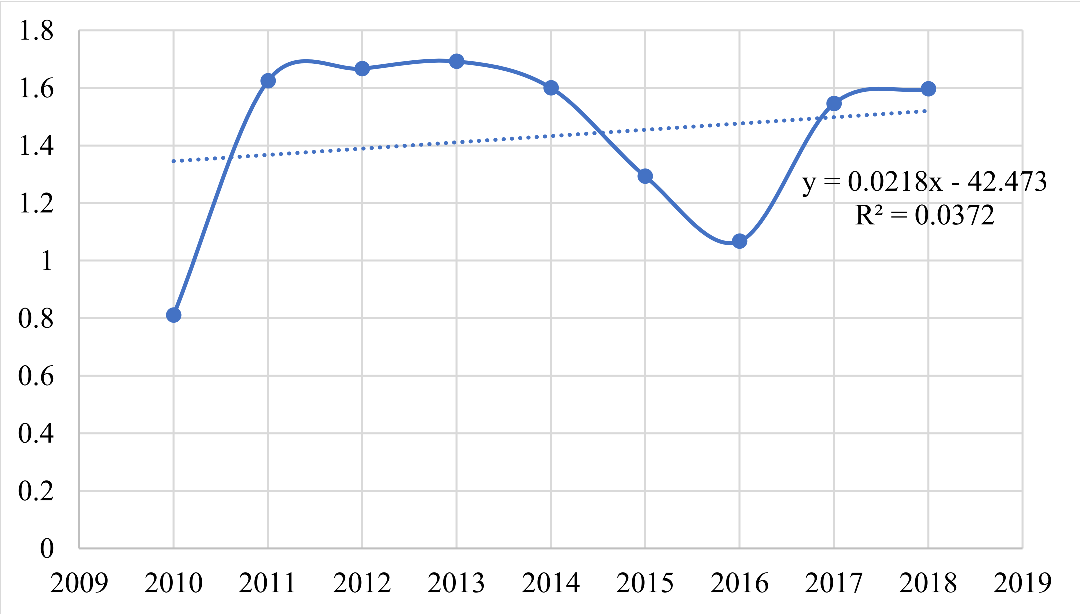

Figure A4. Renewable Capacities in Brunei (GWh)

Based on the graph, a trendline was created to obtain the gradient of the graph. This gradient is then used for extrapolation.

$$y = mx + c \quad (5)$$

$$y = 0.0218x - 42.473 \quad (6)$$

Where x is the year, and y is the renewable energy capacity. When x = 2030,

$$y = 0.0218 * 2030 - 42.473$$

$$y = 1.781\ GWh$$

$$y = 0.001781\ TWh \quad (7)$$

This method applies to all sources from all countries, where data will be represented in the tables below.

Table A2. Renewable Energy Installed Capacity in Indonesia

Indonesia (Year)	Hydropower (GWh)	Biofuel (GWh)	Geothermal (GWh)
2010	17489	6861	9357
2011	12447	7583	9371
2012	12828	7794	9417
2013	16961	7888	9414
2014	15199	8320	10038
2015	13779	8967	10048
2016	18729	8507	10656
2017	18683	9478	12764
2018	17422	9529	13296

Table A3. Renewable Energy Installed Capacity in Malaysia

Malaysia (Year)	Hydropower (GWh)	Solar (GWh)	Geothermal (GWh)
2010	6361	-	1352
2011	8056	-	632
2012	9251	-	1581
2013	11799	54	1241
2014	13541	195	751
2015	15525	277	858
2016	20358	354	598
2017	26717	420	899
2018	26296	440	1756

Table A4. Renewable Energy Installed Capacity in the Philippines

Philippines (Year)	Hydropower (GWh)	Wind (GWh)	Solar (GWh)	Biofuel (GWh)	Geothermal (GWh)
2010	7324	62	-	60	9929
2011	9460	88	-	169	9942
2012	9886	75	-	239	10250
2013	9530	66	-	286	9605
2014	8463	152	-	269	10308
2015	7943	748	139	441	11044
2016	7389	975	1098	831	11070
2017	8889	1094	1202	1118	10270
2018	8662	1153	1251	1210	10435

A4. Solution structure for BIMP-EAGA Cases

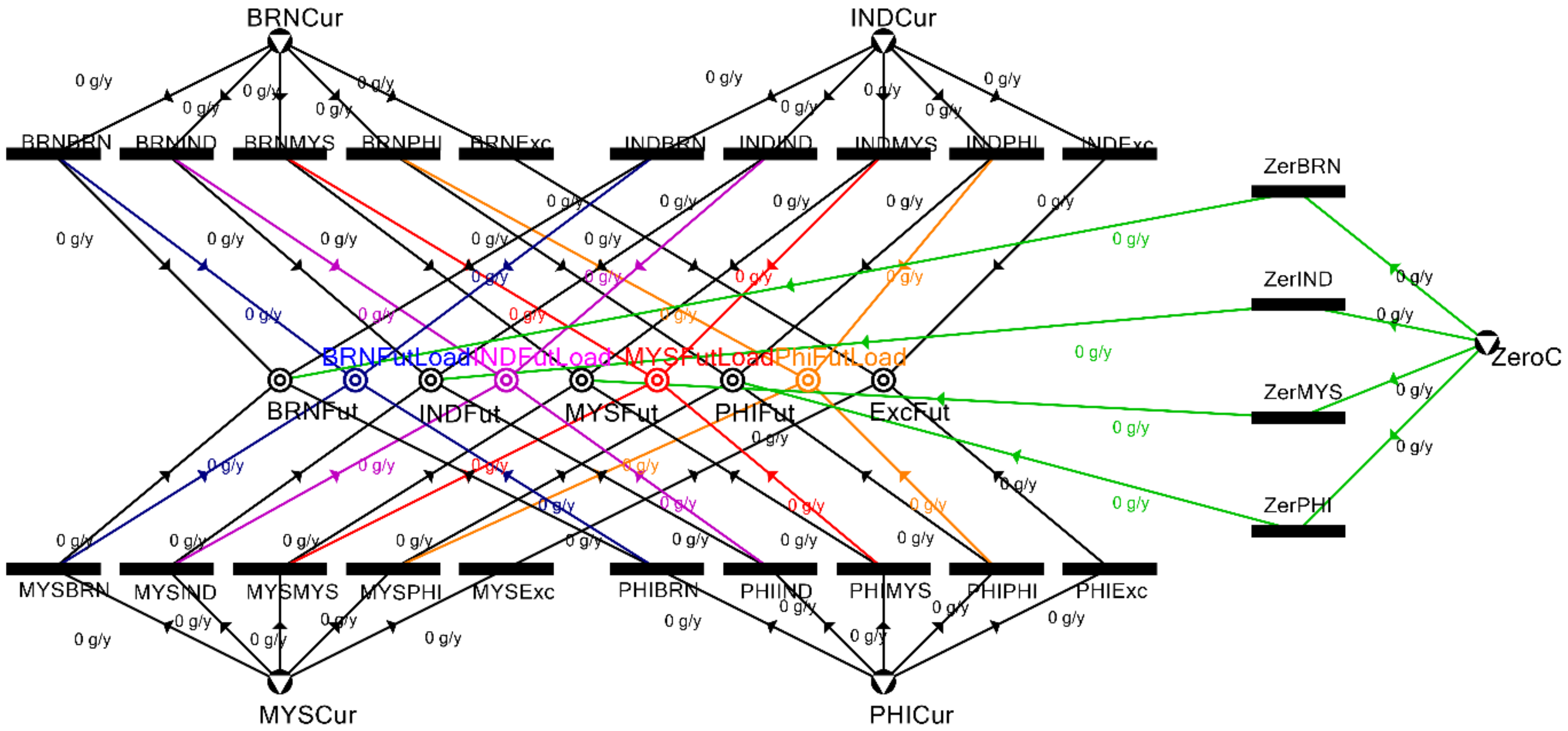

Figure A5. Base Case Maximal Structure

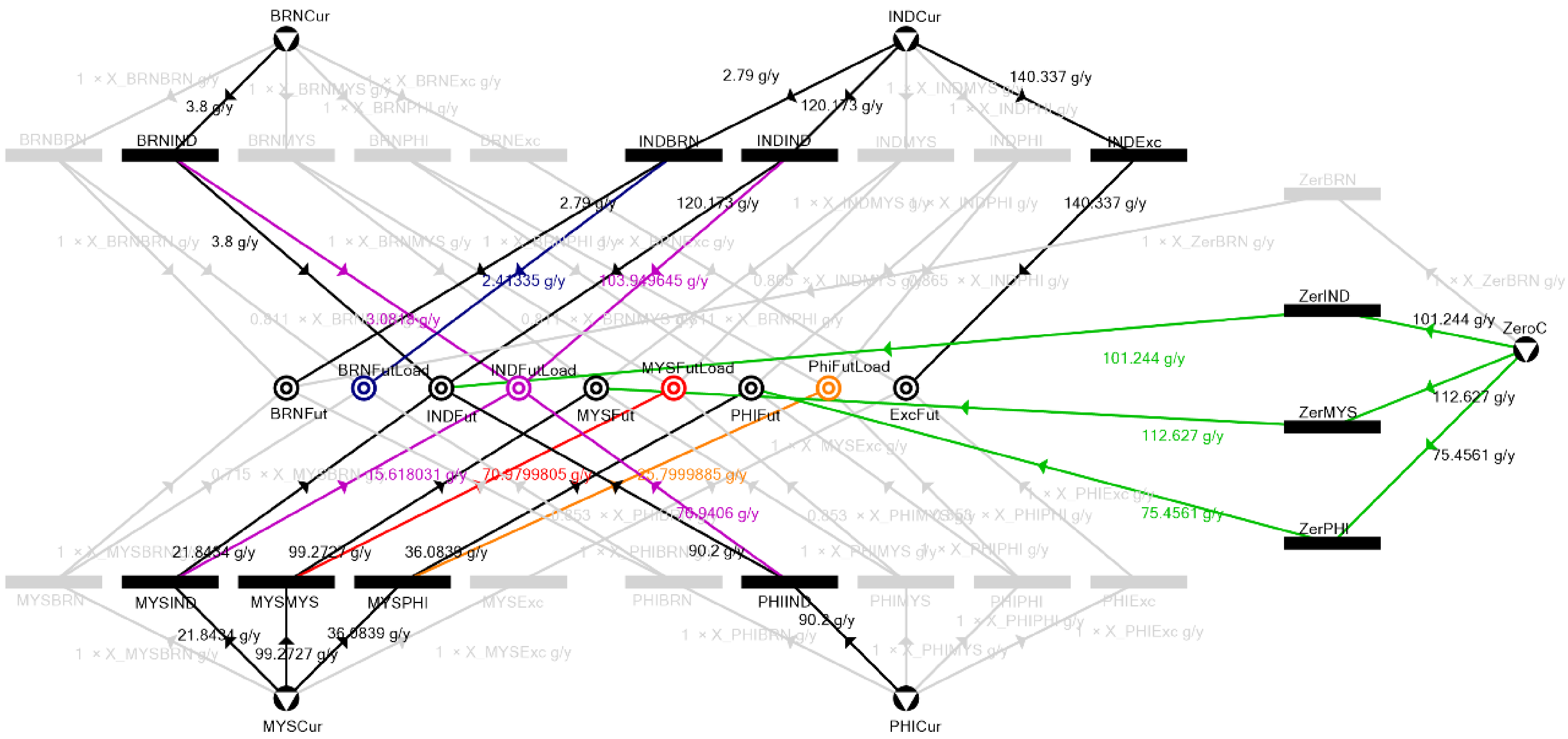

Figure A6. Base Case Solution Structure

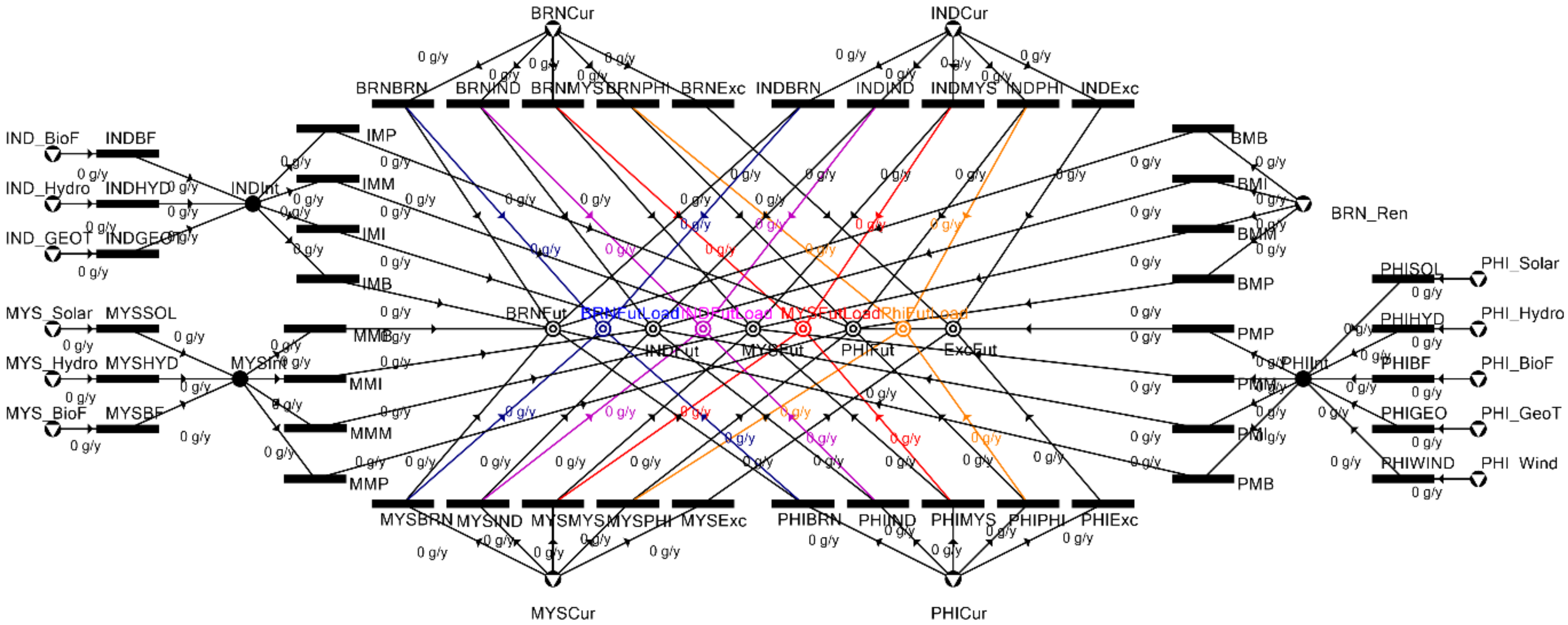

Figure A7. Case 1 and Case 2 Maximal Structure

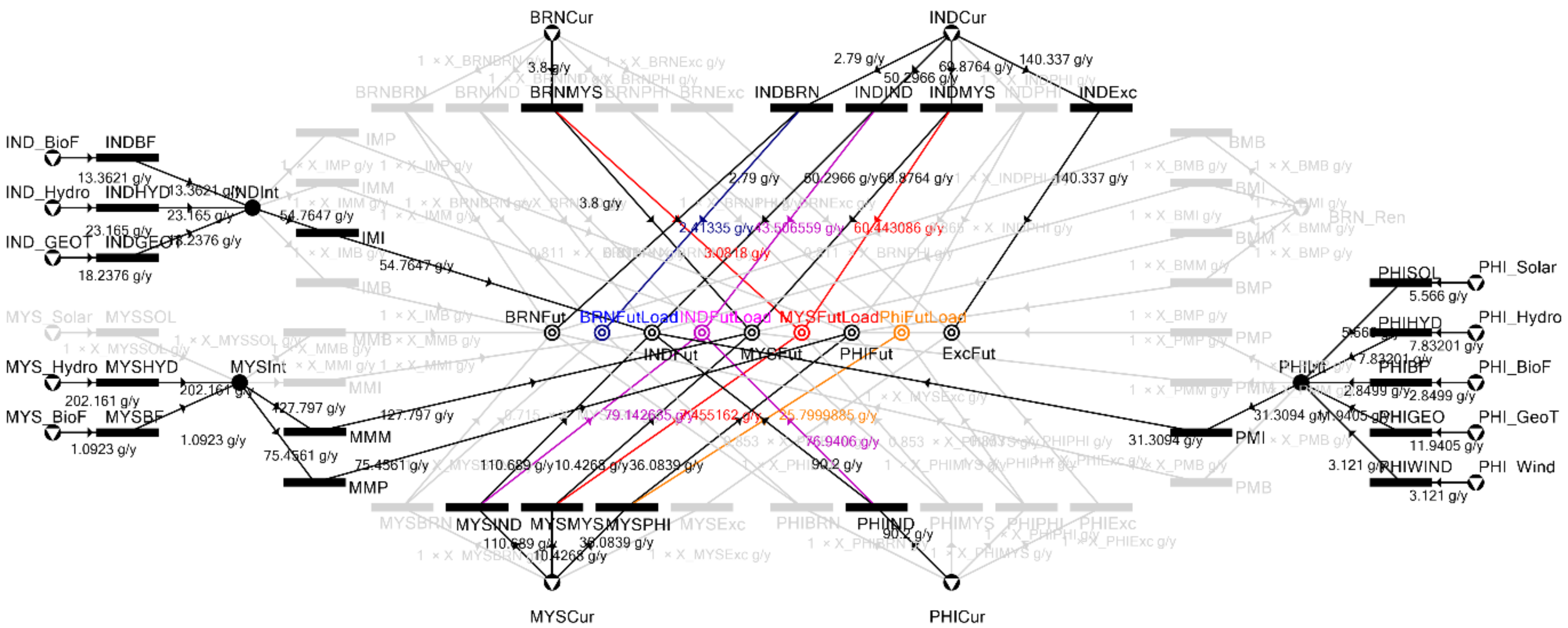

Figure A8. Case 1 Solution Structure

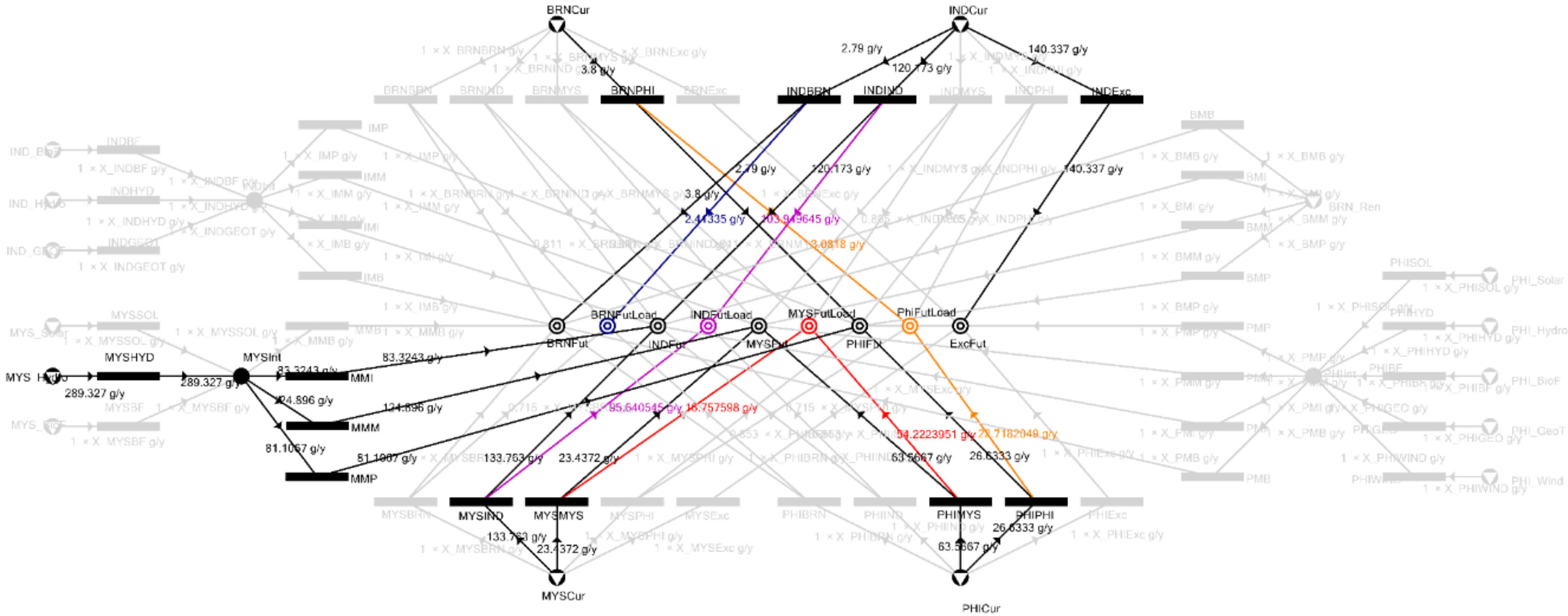

Figure A9. Case 2 Solution Structure

A5. Solution Structure for Canadian Provinces Cases

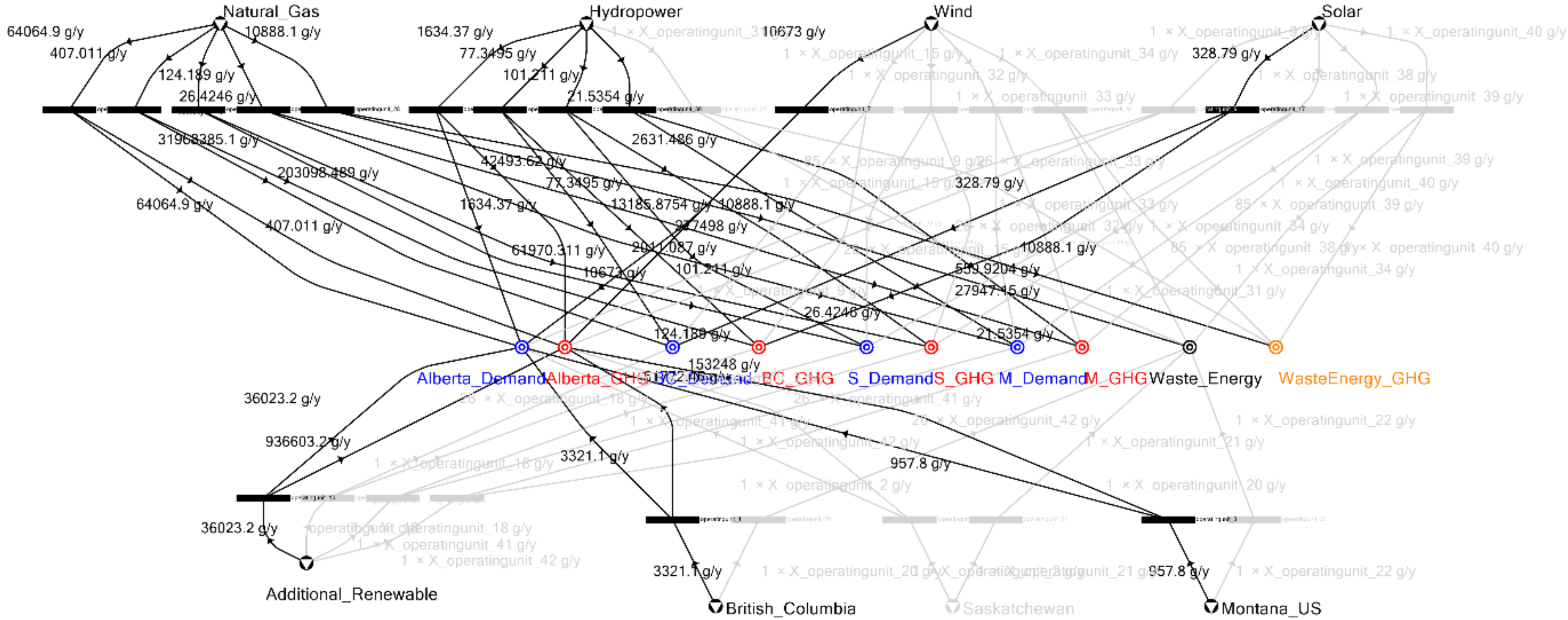

Figure A10. Scenario 1 - Feasible Solution 1

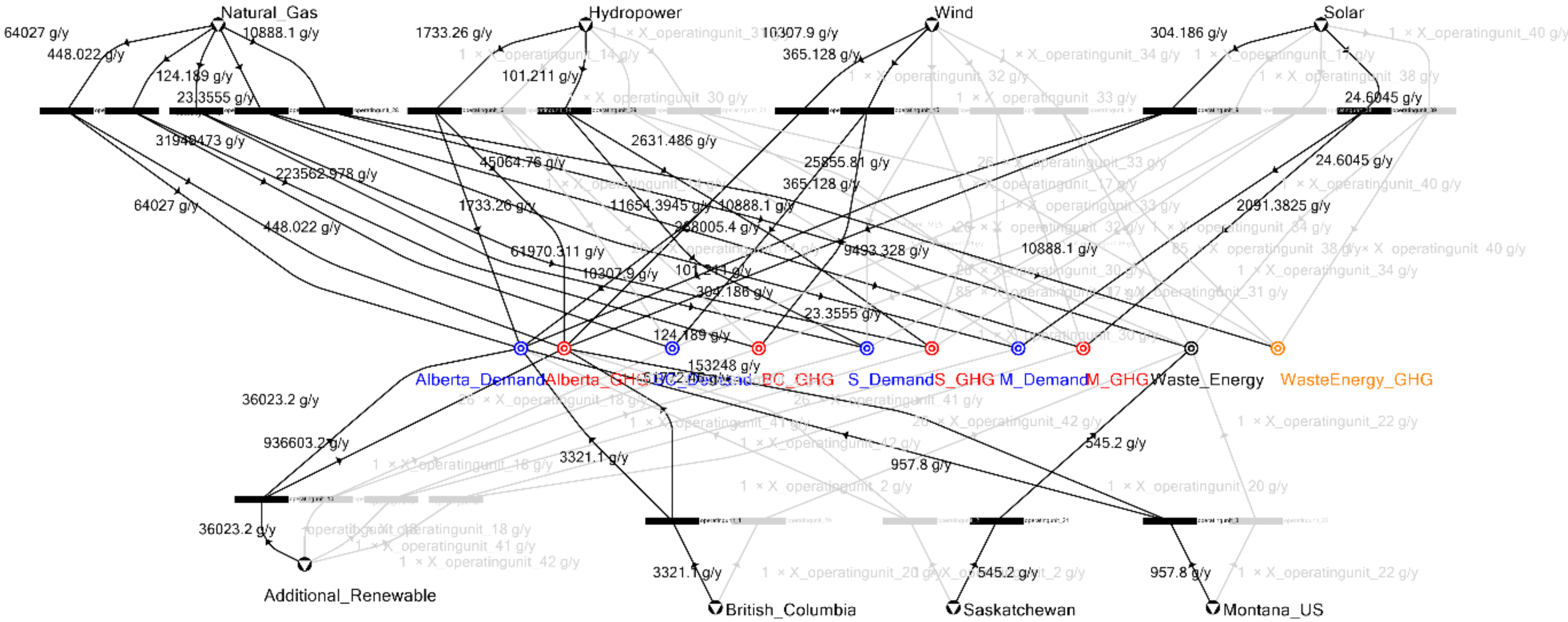

Figure A11. Scenario 1 - Feasible Solution 2

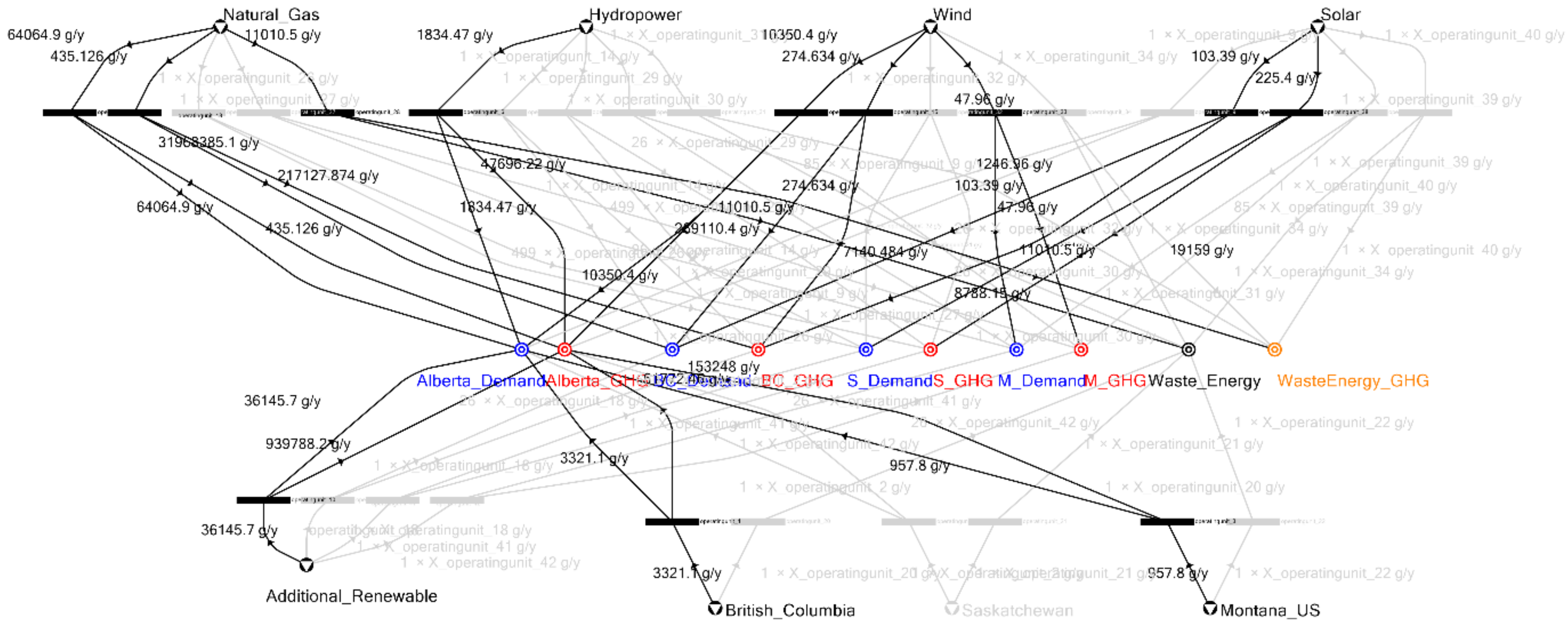

Figure A12. Scenario 1 - Feasible Solution 3

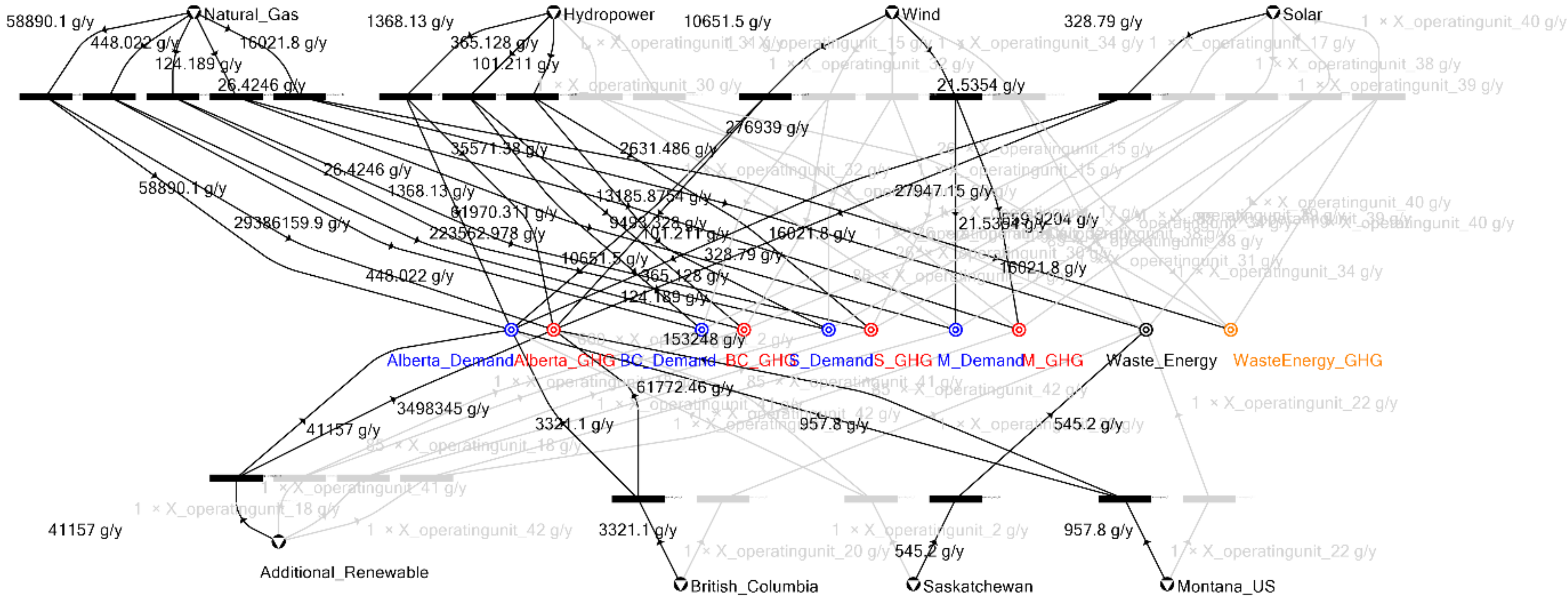

Figure A13. Scenario 2 - Feasible Solution 1

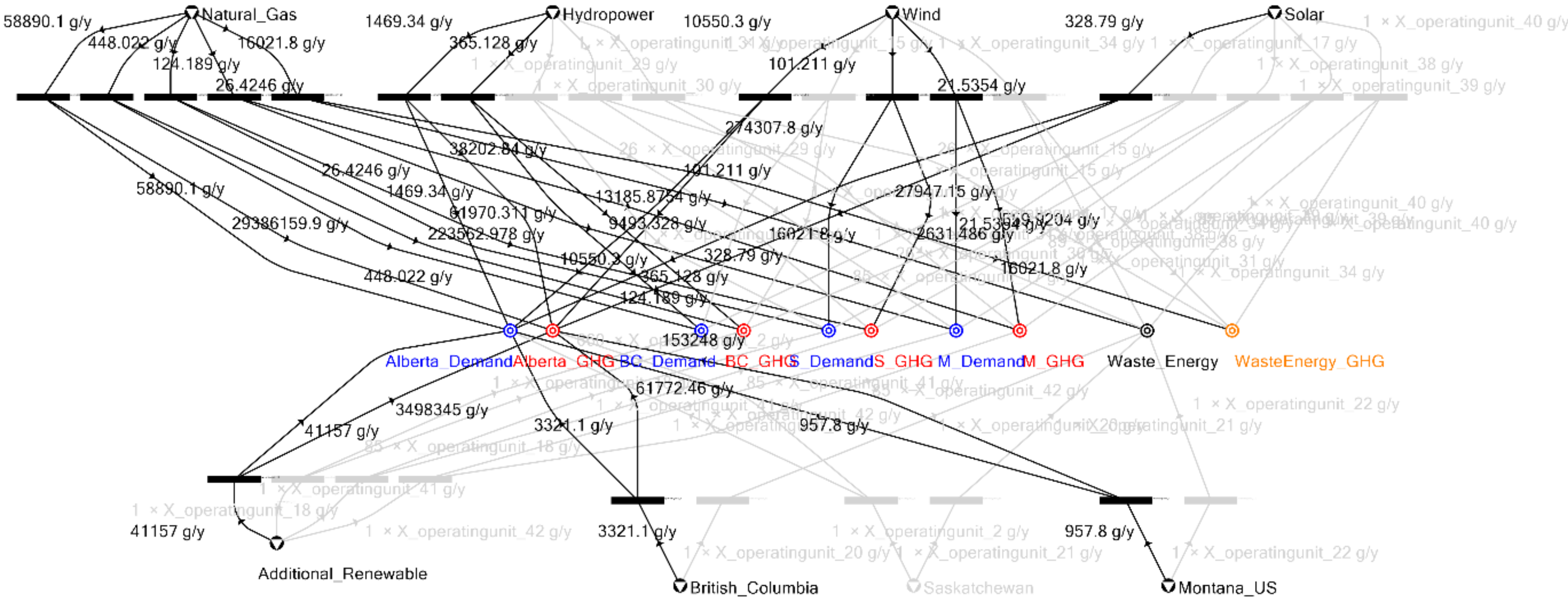

Figure A14. Scenario 2 - Feasible Solution 2

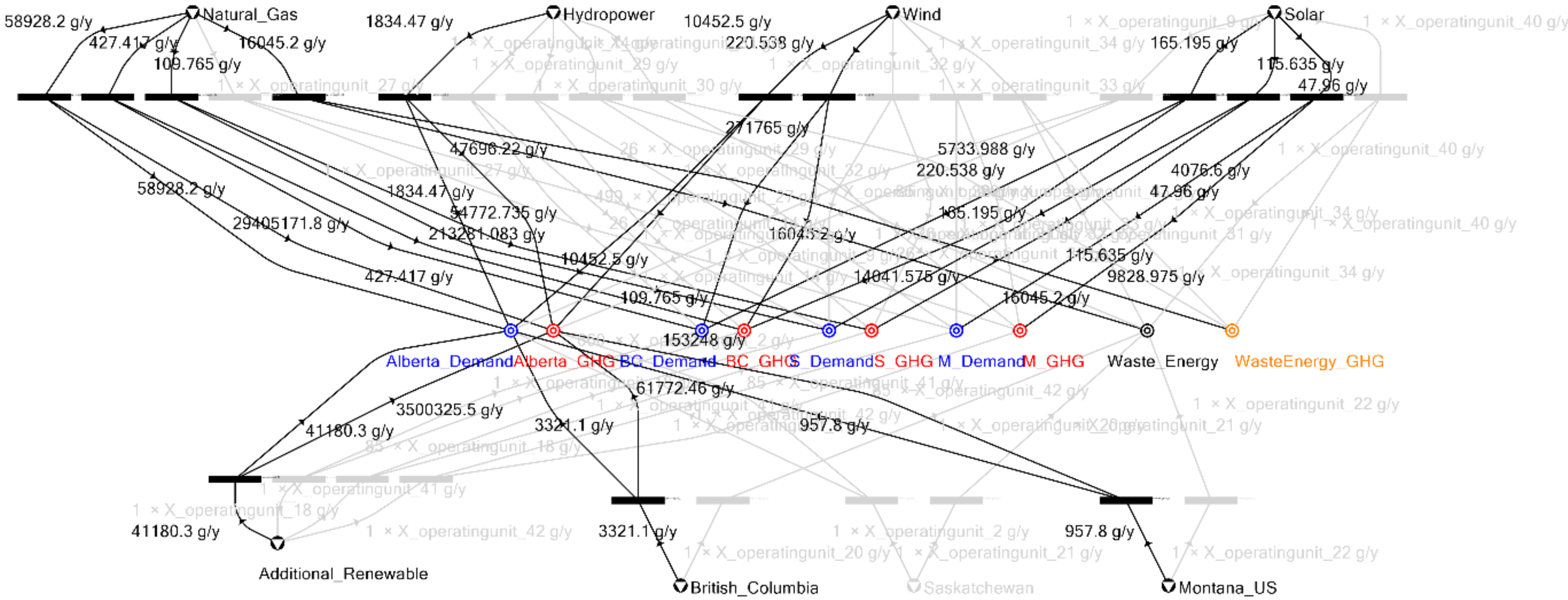

Figure A15. Scenario 2 - Feasible Solution 3

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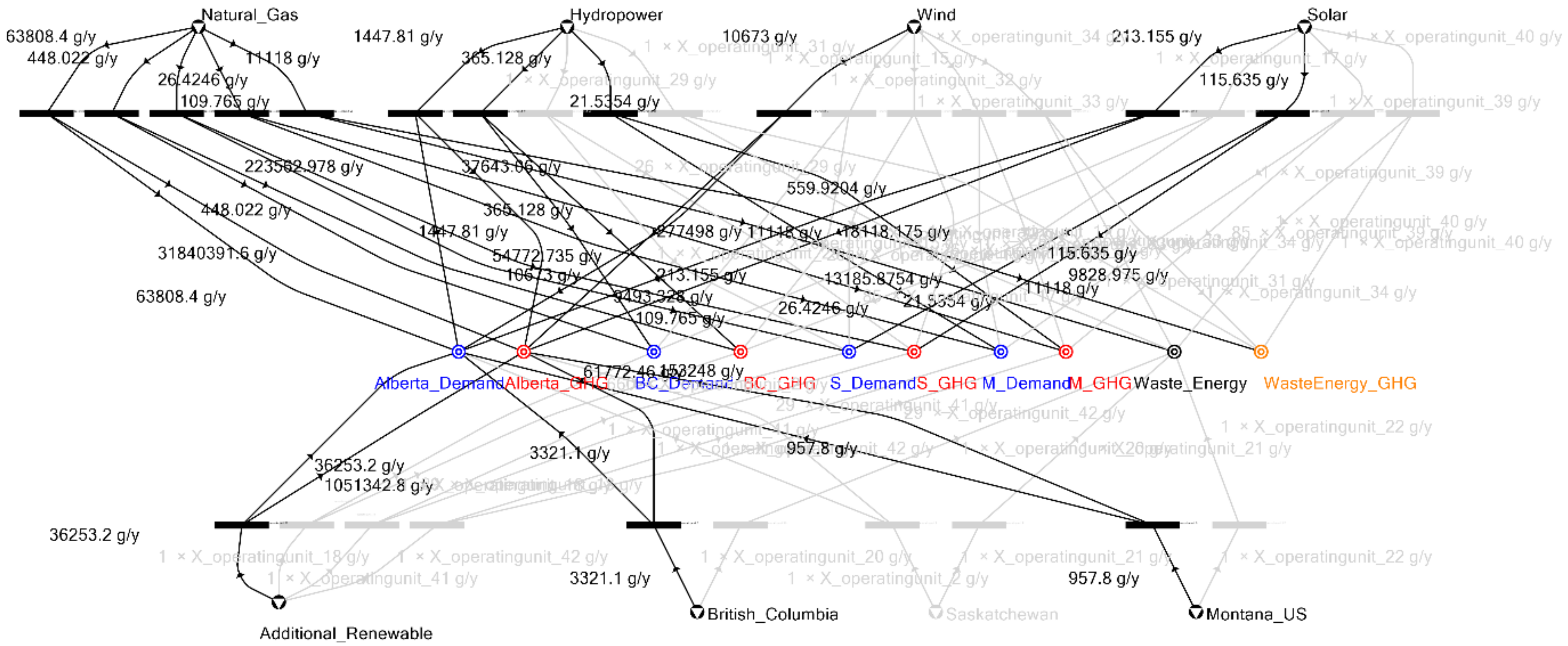

Figure A16. Scenario 3 - Feasible Solution 1

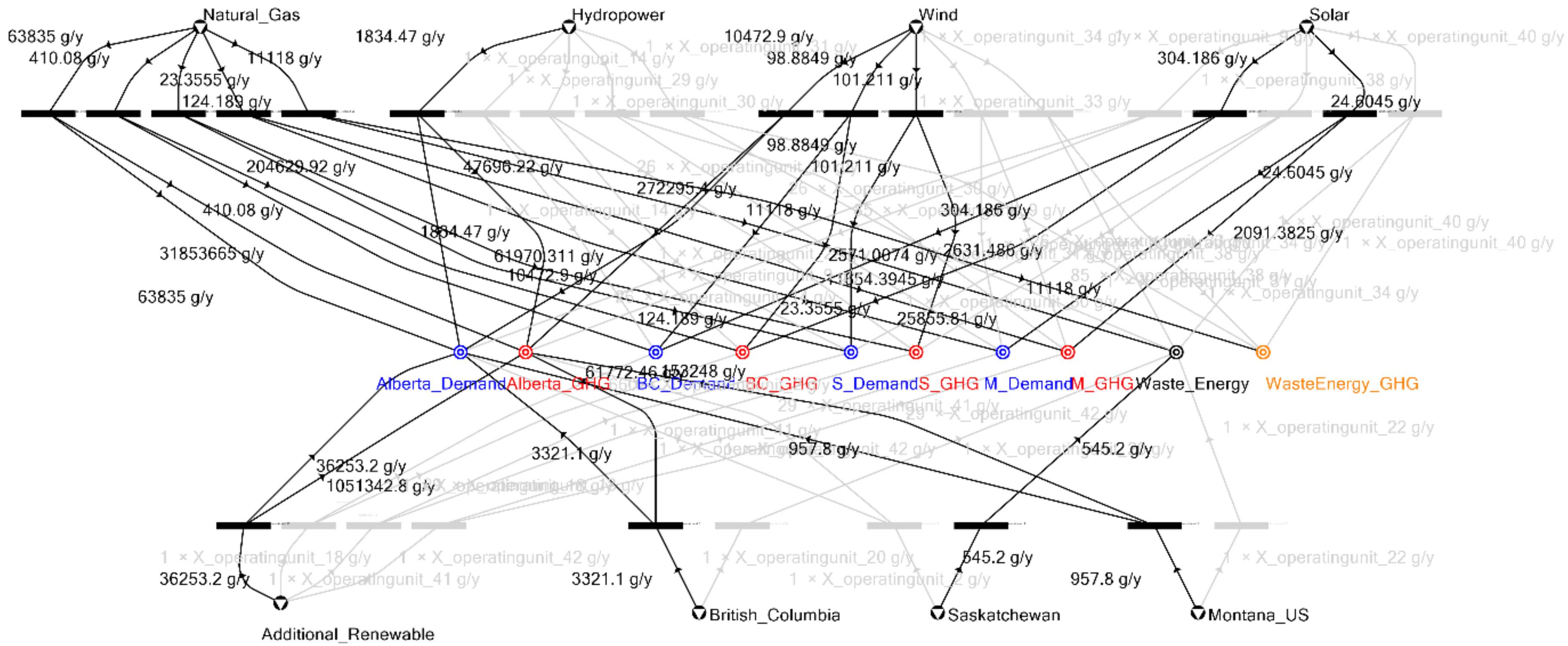

Figure A17. Scenario 3 - Feasible Solution 2

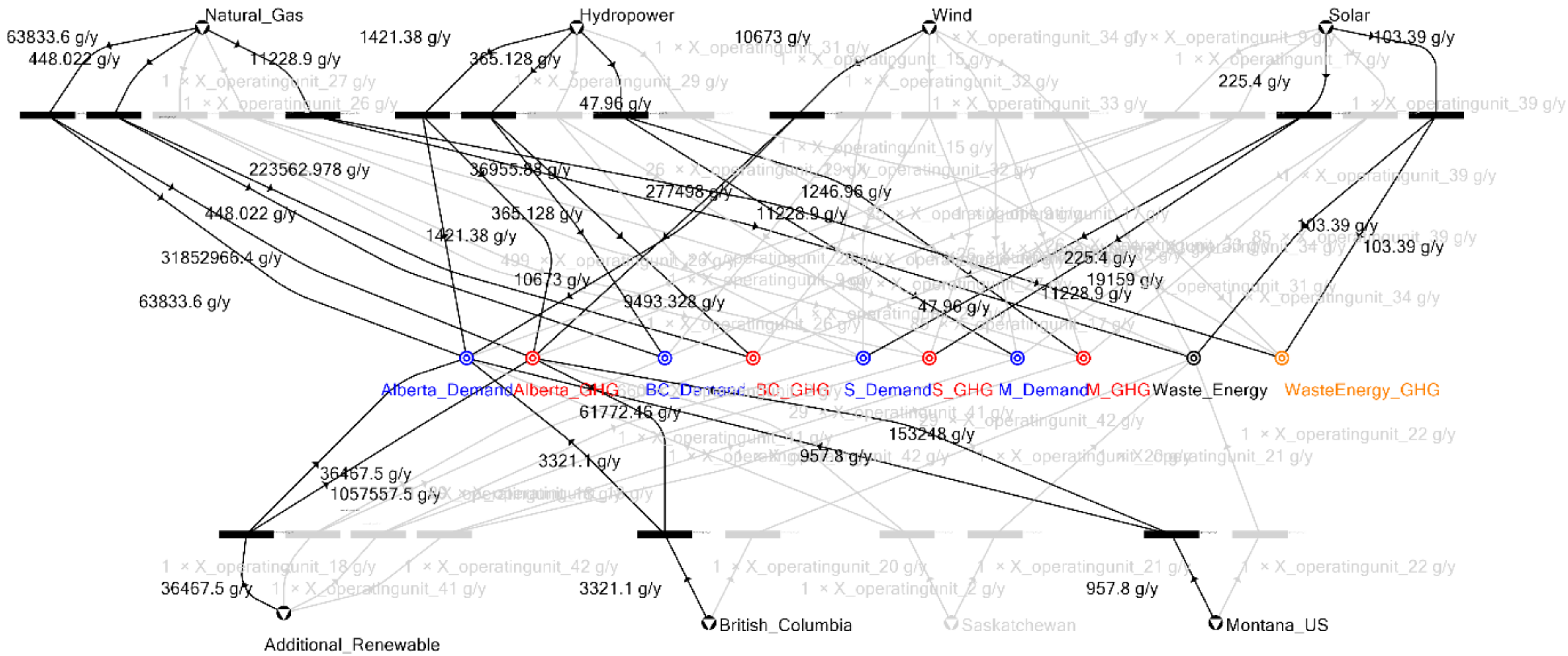

Figure A18. Scenario 3 - Feasible Solution 3

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