Philippine Energy Network Design via an Integrated P-graph and Analytic Hierarchy Process (AHP) Framework

Joshua Bon A. Roco[1,*] and Michael Angelo B. Promentilla[1]
[1] *Chemical Engineering Department, Gokongwei College of Engineering, De La Salle University, 2401 Taft Avenue, 0922 Manila, Philippines*
**Corresponding Author: joshua_roco@dlsu.edu.ph*

Abstract: Sustainable energy networks in the Philippines were designed through P-graph and analytic hierarchy process (AHP). Data used in the simulations came from Department of Energy's Philippine Energy Plan 2018 – 2040 and OpenLCA software. Sustainability was defined as having low global warming potential, low capital expenditures, low electricity costs, high job generations, and high energy self-sufficiency. Relative weights were derived through AHP and integrated in the P-graph to calculate a sustainability score. AHP showed that energy self-sufficiency was the most important criteria among the surveyed experts. Integrated P-graph and AHP simulations showed that optimal and near-optimal solutions relied on geothermal and hydroelectric energy for electricity use while maintaining other energy sources such as coal, oil, natural gas, and biomass for non-electricity demands. Simulations also revealed limitations of P-graph in energy planning such as its inability to alter pre-set rankings in the energy mix and to scale up the model to simulate future years. The optimum energy network resulted to 52% lower global warming potential, 2% higher jobs generated, 27% lower electricity cost, 87% lower capital expenditures and 78% higher energy self-sufficiency than the current scenario.

Key Words: sustainability; P-graph; analytic hierarchy process; energy network design; Philippine energy plan

1. INTRODUCTION

AmBisyon Natin 2040 is a collective long-term vision of the Filipino people in the next 25 years. Its aim is to have no poor Filipino by 2040 or Filipinos having a *"matatag, maginhawa at panatag na buhay"*. As such, the development planning spans across at least four administrations (National Economic and Development Authority, 2016). One foundation in AmBisyon Natin 2040 is the energy sector, which needs to provide affordable and secure energy.

The Department of Energy has recently developed a Philippine energy plan (PEP) that spans from 2018 – 2040. The objectives of the plan are to:

a) increase the production of clean and indigenous sources of energy to meet the country's economic development;

b) decrease energy waste through energy efficiency tools and strategies; and

c) ensure the balance between reliability, affordability, economic growth, and environmental protection.

The Philippines energy supply chain is described through the Sankey diagram below.

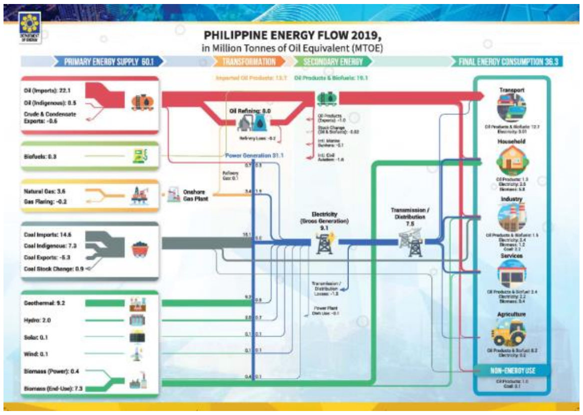


Fig. 1. 2019 Philippine Energy Flows (Department of Energy, 2020)

In 2018, majority of our primary energy supply still comes from coal and oil; and majority of which are imported, garnering an energy self-sufficiency of 50.2% (Department of Energy, 2020).

The energy plan projects the energy demand and supply through two scenarios, the reference scenario (REF) and clean energy scenario (CES). REF projects energy supply chain using business-as-usual strategies while the CES introduces innovations, major investments, and policy shifts.

P-graph is a tool used for process network synthesis (PNS) problems, and has been widely used in urban metabolism design, mostly in energy planning (Walmsley et al., 2017). AHP is a multiple criteria decision analysis that integrates the inherent subjectivity of decisions into a mathematical framework (Promentilla et al., 2018). Together, P-graph and AHP have the potential to improve the sustainability of energy supply networks.

The overall objective of the study was to redesign the 2020 Philippine energy flow through an integrated P-graph and AHP framework to come up with a sustainable energy supply network.

Criteria used to represent the dimensions of sustainability include global warming potential (GWP) for environment, overall capital expenditures (CAPEX) for economy, job generations and electricity cost for society, and energy self-sufficiency (ESS) for overall sustainability. The resulting systems were then compared to the CES and REF scenarios as described in the PEP.

Specific objectives of the project include:

1. identification of most and near optimal supply networks with low GWP, low CAPEX, low electricity costs, high job generations, and high ESS

2. comparison of optimal networks through analytic hierarchy process (AHP) with data surveyed from experts in the energy industry, environment, safety, and health (EHS), manufacturing, and the academe.

Primary energy sources included oil, natural gas, coal, geothermal, hydroelectric, wind, solar, biomass, and biofuels. Meanwhile, energy sinks included energy demands from oil and biofuels, coal, electricity, and biomass.

2. METHODOLOGY

The energy Sankey diagram was modified to be used as the basis of the maximal structure (MSG) in the P-graph. Energy transformation ratios and energy mix were based on the 2019 Sankey diagram. Renewable energy sources were set to unlimited. Meanwhile, P-graph products were CAPEX, jobs generated, GWP, ESS and electricity cost. The P-graph was subjected to constraints such as minimum Jobs, maximum GWP, max electricity cost, and 2020 energy demands, both from REF and CES scenarios.

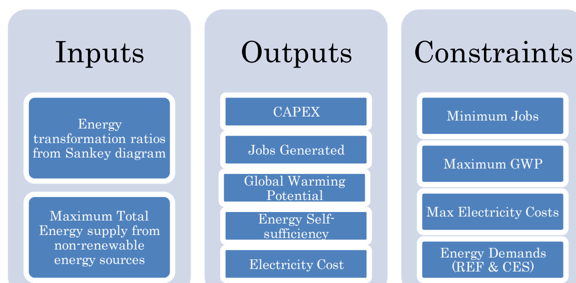


Fig. 2. P-graph data framework

Most of the data sources were from the PEP, except for GWP, which were derived from the OpenLCA software (openLCA 1.10.3) using the ecoinvent databases. GWP considered were the global warming potential over 100 years (GWP 100a).

AHP was used to generate the relative weights of the sustainability indicators. The relative weights were integrated into the P-graph to calculate a sustainability score when indicators are combined. Values per indicator were normalized prior to multiplying to the relative weights.

3. RESULTS AND DISCUSSION

3.1 P-graph Maximal Structure

The MSG of the P-graph is shown in the figure below. The MSG required a total CAPEX of PHP 5.7B, generated 580 MT of CO_2 equivalent and 528 thousand of jobs. Its resulting electricity cost was PHP 6.14/kWh and self-sufficiency of 45.64%.

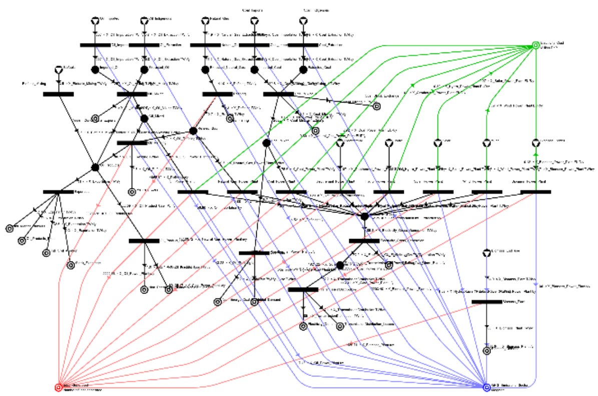


Fig. 3. P-graph Maximal Structure

The MSG is composed of three parts as illustrated in figure 4. Each power plant is connected to five nodes: its source, electricity generation, and the sustainability indicators including job generation, GWP, and electricity cost. The energy supplies were divided into the renewable and non-renewable supplies while the energy demands were divided into electricity and non-electricity demands. The numerical values of each component and their resulting ratios were derived from the 2019 Philippine energy flows.

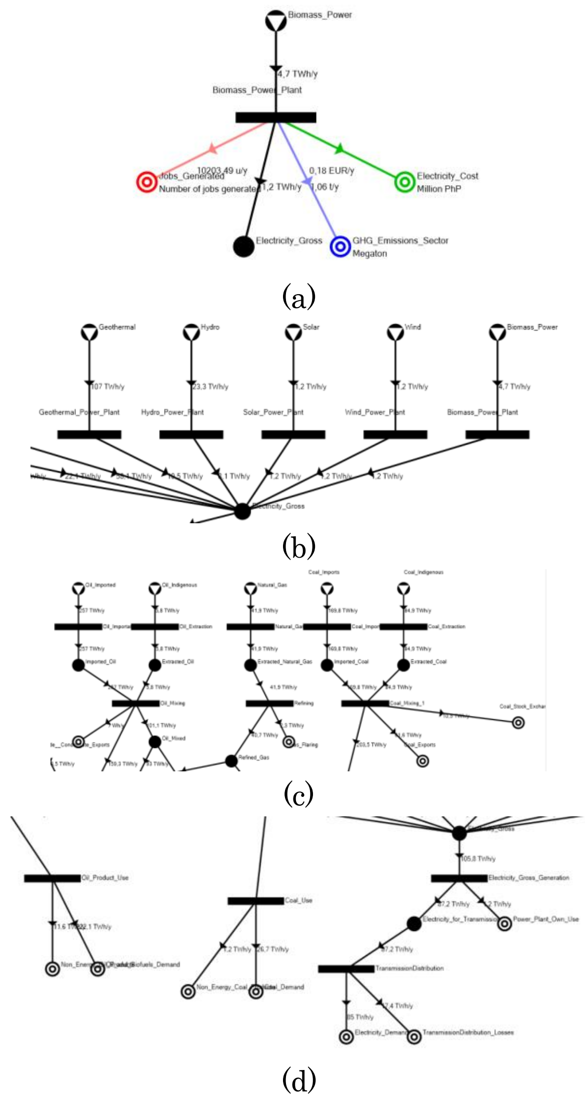


Fig. 4. Parts of the P-graph MSG: (a) power plants, (b) renewable and (c) non-renewable energy supplies, and (d) electricity and non-electricity energy demands

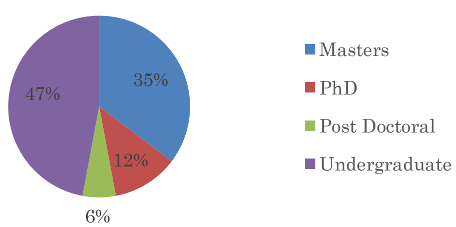
The P-graph assumed various scenarios in the simulation. These assumptions mainly arose due to the lack of reputable data; in return, they have defined the scope and limitations of the study.

- Sankey diagram 2019 approximates the 2020 energy flows. The latest DOE diagram available was from 2019 while most of the data available in the PEP were set to 2020.

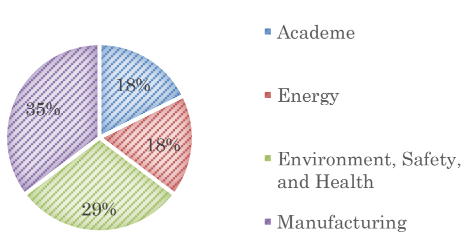
- CAPEX, jobs generated, and electricity costs are linearly proportional.
- There are no existing infrastructures prior to simulation. This was done due to lack of detailed data of existing generation capacities of each energy source.
- Indigenous materials are free but extracting them incur costs.
- Renewable energy sources are unlimited.
- No operational expense (OPEX) for power plants due to lack of reputable data source.
- Cost of import and export of coal and oil are equal. This simplified the simulation since importation and exportation costs highly depend on the importing/exporting country.

3.2 AHP and Sustainability Scoring

Total respondents were 18, with an average age of 42 years old and work experience of 16 years. Respondents came from wide range of experts: from academe, energy, ESH, and manufacturing industries. This balanced the weights from both the perspective of the energy producers, planners, analysts, and end-users.



(a)



(b)

Fig. 5. Respondents' profile: (a) educational attainment and (b) expertise

Among the sustainability criteria, the respondents gave ESS the most importance while CAPEX garnered the least importance. While GWP, jobs, and electricity cost had approximately equal weights. AHP resulted with a 1.0% consistency ratio.

Results also show that energy industry experts prioritize electricity cost and jobs among others. EHS practitioners and those in the manufacturing sector, who can be considered as end-users, prioritize ESS, while those in the academe are more concerned with GWP. None of the considered sectors gave the most priority to CAPEX.

Table 1. Derived relative weights of sustainability criteria from AHP

Criteria	Overall	Energy	EHS	Manufacturing	Acad
GWP	20%	17%	18%	9%	34%
CAPEX	14%	16%	13%	19%	7%
ESS	26%	10%	31%	31%	25%
Jobs Generated	20%	30%	20%	13%	12%
Electricity Cost	20%	27%	18%	28%	22%
Consistency Ratio	1.0%	3%	4%	3%	9%

The results gave a glimpse on how energy producers, analysts, and consumers define energy sustainability in their respective fields. Aside from quantifying the definition of sustainable energy supply network, the results encourage multi-sectoral discussion when conducting energy planning.

3.3 P-graph Simulation Results

The P-graph simulation yielded 153 optimal and sub-optimal networks. For simplification, only 1 optimal and 9 sub-optimal networks were considered in the analyses. Interestingly, REF scenarios comprised the top 6 structures. The main reason for this was the high electricity costs for the CES. The PEP states that increase in the price is due to the "increase of renewable energy in the mix" (Department of Energy, 2020).

Table 2. Optimal and near-optimal P-graph simulation results

	Score	Scene	Electricity (PHP/ kWh)	GWP (MTC O_{2e})	Jobs	CAPEX (BPHP)	ESS (%)
1	84.8%	REF	4.50	279	539,313	824.7	65
2	84.5%	REF	4.50	279	528,194	824.7	65
3	83.5%	REF	5.00	283	803,332	824.7	68
4	82.0%	REF	5.50	287	1,067,350	824.7	70
5	80.6%	REF	5.86	290	1,257,440	824.6	72
6	80.4%	REF	6.00	291	1,331,370	824.6	72
7	79.8%	CES	5.00	280	576,423	808.2	66
8	78.5%	CES	5.50	284	843,053	808.2	69
9	78.9%	CES	5.00	279	528,194	808.3	66
10	77.0%	CES	6.00	288	1,109,680	808.2	72
Versus MSG (%)			+14	-51	+63	-88	+95

On the average, the top 10 networks gave 14% lower electricity costs, 51% lower GWP, 63% higher jobs generated, 88% lower CAPEX, and 95% higher ESS.

The table below summarizes the materials, products, and infrastructures used per network structure.

Table 3. Optimal and near-optimal P-graph simulation results

	Raw Material Transformation						Non-Elec			Electricity Use							
Structure	Biofuels	Indigenous Coal	Imported Coal	Indigenous Oil	Imported Oil	Natural Gas	Biomass Use	Coal Use	Oil Product Use	Biomass	Coal	Geo	Hydro	Natural Gas	Oil	Solar	Wind
1		X	X	X	X	X	X	X	X			X	X				
2		X	X	X	X	X	X	X	X			X	X			X	
3		X	X	X	X	X	X	X	X			X	X				
4		X	X	X	X	X	X	X	X			X	X				
5		X	X	X	X	X	X	X	X			X	X				
6		X	X	X	X	X	X	X	X			X	X				
7		X	X	X	X	X	X	X	X			X	X				
8		X	X	X	X	X	X	X	X			X	X				
9		X	X	X	X	X	X	X	X			X	X			X	
10		X	X	X	X	X	X	X	X			X	X				

Significant GWP savings and increase in ESS came from the total shift of electricity supply from coal and oil to renewable, such as geothermal and hydroelectric energies. Since oil and coal power plants generated the most GWP and required all importation activities, removing them as electricity sources improved GWP and ESS drastically. On the other hand, investing in geothermal energy produced the most jobs per TWh, mostly contributing to the 63% increase in jobs generated. Meanwhile, removing the biomass power plant, which has the highest CAPEX per TWh, contributed to the large CAPEX savings.

While only renewable energies were considered for electricity use, coal, oil, natural gas, and biomass were still part of the energy system because of their non-electricity energy demands. All the oil and coal extraction and imports were used for oil-products and coal use. Extracted natural gas were all used for oil refining. Finally, biofuels were not considered in the oil-product use network because of its high CAPEX cost.

3.4 Limitations of P-graph

Limitations of simulations using P-graph were observed. One is that the rankings in the energy mix cannot be altered since the reference energy flows have already a pre-set energy mix. For instance, although wind and solar cost the least CAPEX, produce the least GWP and have 100% ESS, the resulting renewable energy mix did not favor them in most of the solutions. Not only is their electricity cost significantly higher than others, but also the reference Sankey diagram already had them rank the least energy shares (0.6%).

The 2020 energy network and their ratios cannot be used to plan the energy mix in 2040. Even if the energy supply and demand were scaled to 2040 values, maintaining the energy conversion ratios would fail to generate solutions. The ratios will blow up because they are assumed linear. The network generated solutions when constraints were removed, but this would render the model unrealistic. Such limitations were defined by Urbanucci (2018) as failure to account nonlinear effects and time periods at once, and the risk of high dimensionality. There are available techniques to address the limitations, such as decomposition methods, dimensionality reduction, and rolling-horizon technique.

Limitations recommend that planning for the 2040 energy mix using P-graph would require updating the energy demand and supply, as well as projecting the energy flow ratios.

3.5 Optimal Energy Network

The optimal energy network is shown in the figure below.

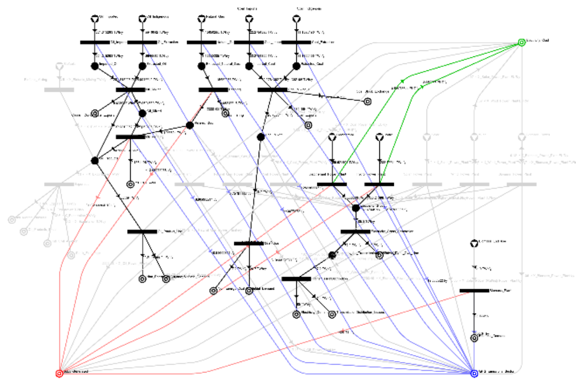


Fig. 6. Optimal P-graph Network

The optimal network yielded 52% lower GWP, 2% higher jobs generated, 27% lower price of electricity, 87% lower CAPEX and 78% higher ESS.

Table 6. Sustainability criteria results of the optimal energy network

Sustainability Criteria	Results	Comparison
GWP ($MTCO_2e$)	278.92	52% lower
Jobs Generated	539,313	2% higher
Electricity Cost (PhP/kWhr)	4.50	27% lower
CAPEX (MPhP)	824,730	87% lower
ESS (%)	58	78% higher

4. CONCLUSIONS

The study used P-graph and AHP in the design of sustainable energy supply network in the Philippines. The sustainability score was defined through AHP with the objectives of having low GWP, low CAPEX, low electricity costs, high job generations, and high ESS. AHP showed that generally, ESS was prioritized among other criteria, and CAPEX the least.

The P-graph MSG of the 2020 Philippine energy flows was constructed under assumptions arising from data limitations and simplicity of analysis. The simulations also revealed the limitations of P-graph in energy planning: scaling functions were assumed linear, which deviated the solutions from actual scenarios and energy mix solutions were limited to the reference energy flow ratios. Nonetheless, the optimal and near-optimal solution showed that a sustainable energy supply network relied on renewable energy (i.e. geothermal and hydroelectric) for electricity use while maintaining other energy sources such as coal, oil, natural gas, and biomass for non-electricity demands. Implementing the ideal optimum network would yield 52% lower GWP, 2% higher jobs generated, 27% lower electricity cost, 87% lower CAPEX and 78% higher ESS.

5. REFERENCES

Department of Energy. (2020). Philippine Energy Plan 2018-2040. Department of Energy.

National Economic and Development Authority. (2016). About Ambisyon Natin 2040. Retrieved from Ambisyon Natin 2040 Website: https://2040.neda.gov.ph/about-ambisyon-natin-2040/

Promentilla, M. A., Aviso, K., Lucas, R., Razon, L., & Tan, R. (2018). Teaching Analytic Hierarchy Process (AHP) in undergraduate chemicalengineering courses. IChemE, 34-41.

Urbanucci, L. (2018). Limits and potentials of Mixed Integer LInear Programming methods for optimization of polygeneration energy systems. Energy Procedia, 1199-1205

Walmsley, T., Jia, X., Philipp, M., Nemet, A., Liew, P., Klemes, J., & Varbanov, P. (2017). Total Site Utility System Structural Design Using P-graph. Chemical Engineering Transactions, 31-36.