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Segmented model of the United Energy Market of the Eurasian Economic Union and Cross-border Transmission Lines Expansion

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***Abstract*—In this paper, we investigated the dynamics of Electrical transmission interconnection among countries of the newly formed Eurasian Economic Union (EEU). Though, the union was formed primarily for the basis of trade and labor supplies, the authors felt there may be a good investment opportunity if the countries decide to have a common electricity market. Intensive study was done on the power market existent in each country and the plans of expansion each country is currently pursuing. Russia's electricity generation and consumption was more than 6 times greater then the production and consumption of all the other 4 countries combined. Then, the transmission lines built during the soviet era were also examined and new opportunities for further collaboration were identified. A generation and transmission expansion planning model was finally developed to investigate the impact of inter-connectivity among the EEU countries. Finally, results and discussions are presented to highlight our findings.**

***Index Terms*—Electricity generation, consumption, transmission, inter-connectivity, line capacity, planning**

NOMENCLATURE

Sets

CT	Set of all countries in EEU
J	Set of all nodes i.e. generation and/or demand locations
L	Set of all lines: existent and proposed
G	Set of all generation sources
M	Set of all months

Parameters

L_{max}	Maximum Line Capacities
G_{ij}	Maximum generation Capacities
L_{ij}	Average load per month per node
h	Amount of hours in each month
GC_{ij}	Variable generation cost per node
TF_{ij}	Fixed Transmission cost per node
TV_{ij}	Variable Transmission cost per node

Variables

x_i	Line construction decision variable
fl_i	Final line capacity if line is built
g_{ij}	Generation per month by source
C_G	Overall Generation Investment cost
C_T	Overall Transmission Investment cost
TC	Overall Investment Cost

I. INTRODUCTION

THE current state of power systems begs the question of the benefits of interconnections between multiple power sources. The debate between having a distributed power system and having a centralized one has many questions to answer, starting with the technical aspect of efficiency, feasibility, and reliability. Then there are the economic incentives of having interconnection between grid within the same country or among multiple countries.

In 2014, the Eurasian Economic Union or the EEU was established, creating free movement of goods and trade across the countries in the union which currently include Russia, Armenia, Belarus, Kazakhstan, and Kyrgyzstan. This union as well as existing transmission lines extending between these countries give rise to an opportunity of a single electricity market across the five nations. Achieving that goal requires an extensive study of the power system and the power market of these countries, their regulations, policies, and future goals. As well as current standing agreements on cross-border transmission lines. Following that a modelling approach for the existing power systems as well as transmission line expansion optimization. Then collecting data to feed into that model which can be a difficult process.

II. LITERATURE REVIEW

A. Power sector review

Each country has its own power sector challenges and demands, with different regulation and approaches. for the most part, the five countries have a somewhat traditional market with a mostly state owned monopoly. To have a united energy market between these different countries will require a lengthy process of policy and regulation discussion and negotiation. But luckily the EEU countries seem to be heading towards a direction of liberalizing the market for the most part.

1) Russia: [1] Russia is by far the largest of the five countries in all aspect of the power system. The capacity of the Russian grid, the consumption levels, the reach and the transmission distances dwarf that of the other countries, which makes it a deciding factor when it comes to this study.
Power generation in Russia is mostly from fossil fuel, with 48% from gas, 16% from coal. The rest comes from hydro at 17% and nuclear at 18%. The current capacity exceeds demand at around 250GW of generation capacity compared to around only 180GW of demand.
Russia is already well connected with the other four countries with transmission agreements. In Russia itself there is a well-established wholesale and a retail electricity market which still lacks in competition in the capacity and generation side of things. Regulation for renewable plants are already in place with incentives and special tariffs.

2) Kazakhstan: [2] The power sector in Kazakhstan is mainly reliant on fossil fuel for power production at 66% of generation from coal and 21% from gas.While generation is not falling below demand levels, Kazakhstan faces problems with the distribution of power generation. While most of the generation is in the northeast part of the country and most of the demand is located in the southeast. The transmission between north and east is congested and Kazakhstan has to rely on imports from Russia to overcome the deficits. Kazakhstan also relies on imports to regulate the grid frequency. The country has existing bi-directional transmission lines with Russia and Kyrgyzstan.
The power system is divided into a national transmission grid which is government owned, regional distribution companies, and independent electricity producers.

3) Krygzstan: [3], [4] Kyrgyzstan has 87% of its power generated from hydro and the other 13% mostly from coal. The current condition of the power system is weak, with problems of old and under-maintained equipment with 45% of the power generation capacity commission in the Soviet era. The country has existing import agreements with Kazakhstan.
For the past five years, the power sector in Kyrgyzstan has been going through a reform process which is aimed to solving the sectors financial and technical problems. The power market is a natural monopoly on the transmission and distribution levels. There are some private wholesale buyers and sellers of electricity but the government controls almost 95% of the energy sector companies.

4) Armenia: Armenia has an almost equal split of generation between fossil, hydro and nuclear. But it relies on gas and nuclear imports from Russia and Iran.Armenia is a net exporter of electricity with current plans for the construction of transmission lines connecting to Iran, Georgia, Turkey and Russia.
The power market in Armenia is a state monopoly except for the generation part where its a mix of state owned and private plants. Wholesale market liberalization started recently in 2017-2018.
Armenia in particular poses a quandary since its a possible area of overlap between the EEU and the EU's electricity markets. [5]

5) Belarus: Electricity generation in Belarus is dominated by gas power plants at around 90% of consumption, while the other 10% are imported from other countries including Russia, almost all of the gas is also imported from Russia.
The electricity market structure in Belarus is a vertical monopoly controlled by the state with recent consideration of market reform.

III. Mathematical Model

Cross border generation and transmission lines expansion planning is not a new subject. Several authors have proposed different formulations for investigating this themes. For the generation and transmission planning problem, we adapted the formulation from [6] and used a planning time-line of 10years.

The objective function is co-optimizing the transmission investment cost and generation cost over the planning period.

$$Min \;\; TC \tag{1}$$

$$TC = C_T + C_G \tag{2}$$

$$C_T = \sum_{i \in L} fl_i.TV_{ij} + x_i.TF_{ij} \tag{3}$$

$$C_G = \sum_{m \in M} h_m \sum_{i \in N} \sum_{t \in T} g_{imt}.GC_{imt} \tag{4}$$

$$L_{ij} = \sum_{t \in T} g_{ijt} + \sum_{l \in L} fl_l \tag{5}$$

$$0 \leq g_{ijt} \leq P_{nt}^{max} \tag{6}$$

$$-Fl_l \leq fl_{ls} \leq Fl_l \tag{7}$$

$$x_i.Fl_l^{min} \leq Fl_l \leq x_i.Fl_l^{max} \tag{8}$$

$$g_{ijt} \leq p.P_{1t}^{max} \tag{9}$$

$$x_i \in 0, 1 \tag{10}$$

Equation (1) states the objective function which is fully described in (2) as the sum of the generation and transmission investment cost. The transmission investment cost given in (3) is sum of the transmission investment cost for existing lines based on the power flow through them and the fixed investment cost if the lines are constructed. The generation cost (4) is the variable cost of generation based on the power source. Equation (5) describes the power balance while (6) sets the limit on the maximum amount of power that can be produced from each generating source. Constraint (7) set the bounds on the line flow. The negative basically imply a counter flow. (8)

sets the limit if a line is constructed while (9) is meant to put a minimum percentage of fossil fuel usage. This was used because the variable generation cost of renewables are very low. Sometimes, the cost of fossil fuel is as high as 1500% of renewables. In order to avoid the solver giving inoperable solutions, we used this constraint. (10) sets the decision to build or not build the line as a binary variable.

IV. Solution Approach

There are series of ways to think about the solution to this problem. In this work, we considered a number of them. Firstly, We used the static year to year optimization approach. This was discussed in [7] and the idea is optimizing a year at a time without giving so much consideration to future occurrences. This future happenings could be change in price of oil, technology, security, operation and maintenance costs etc. The reasons why the authors think this might be a valid idea is because:

- Oil prices do not follow any mathematical progression. Prices might be high next year and low the year after. Thus, the price changes will even out.
- Electricity consumption might increase but this is always followed by a commensurate increase in generation investment. Even countries that do not have concrete plans also ensure some generation investment once in a few years.
- The technology cost, especially renewable technology, is continually on the decrease. This is expected to continue. This factor also sees to other unforeseen costs in operation, maintenance and probably security costs.

Another good reason why we used this approach is the little computational effort required while solving the "year at a time" model.

We also investigated the idea of demand projection at the end of the planning period (10 years in our case). How was this done?
Using classical inflation rate, population growth of our study locations, climate and other environmental indicators, we made a forecast of how much the electricity demand will be at the end of the 10 years. Using this new demand data, we ran the planning algorithm as a single period and reported results obtained.

Other approaches the authors examined include: 1) fixing generation (assuming no generation expansion would not be required during the planning horizon) while focusing on transmission expansion only.

V. Data

The countries in the EEU are Armenia, Belarus, Kazakhstan, Kyrgyzstan and Russia. Based on the dynamics present in each country, we identified seven (7) distinct nodes which comprise two (2) in Russia and Kazakhstan and one (1) in each of the other countries. For Russia, the western part is chosen as a node while the parts of Siberia is the other node. For Kazakhstan, the capital (Nur-Sultan) where the majority of the generating capacity resides is chosen as a node while the southern part where most of the demand is (including Almaty, close to the border with Kyrgyzstan) is the other node. Though there exists North-South connections, these are insufficient to meet demand. Figure 1 shows the map of the EEU member countries, their relative positions and some of the existent and proposed transmission lines.

Fig. 1. EEU map with generation and consumption nodes

For good visual cues and to see the positions of the countries relative to each other in terms of generation (figure 2) and consumption (figure 3), we present the production and consumption curve. Additionally, we present the generation mixes (figure 4) as well as the renewable energy mix (figure 5) of each countries

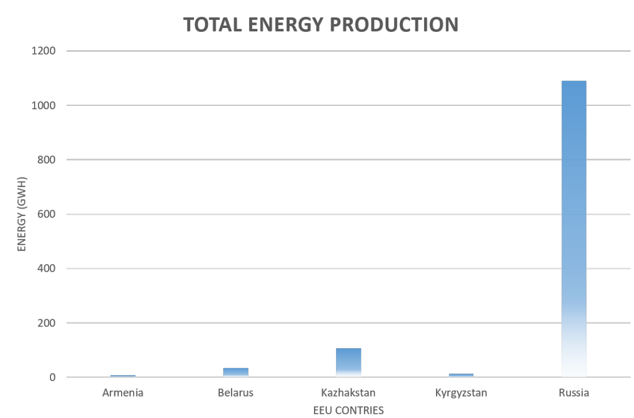

Fig. 2. Energy Generation of EEU Countries

Judging from the peculiarity of the member states of the EEU and as shown in figures 4 & 5, we decided to have just three (3) classes of generation sources.

1) Fossil fuels consisting gas, oil and coal
2) Hydroelectric generation
3) Other renewables consisting wind, solar PV, bio-fuels etc

For transmission, table below [1] gives the distance between all nodes (straight line distances) as well as the capacity of lines for junctions where there are existent capacities. RU1 and

[1]In the table, D - Distance between the two countries, E. C. - "Existent Capacity" and Max C. - "Maximum line Capacity" respectively

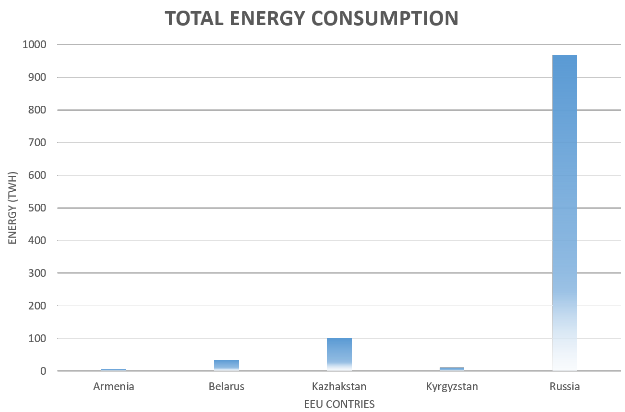

Fig. 3. Energy Consumption of EEU Countries

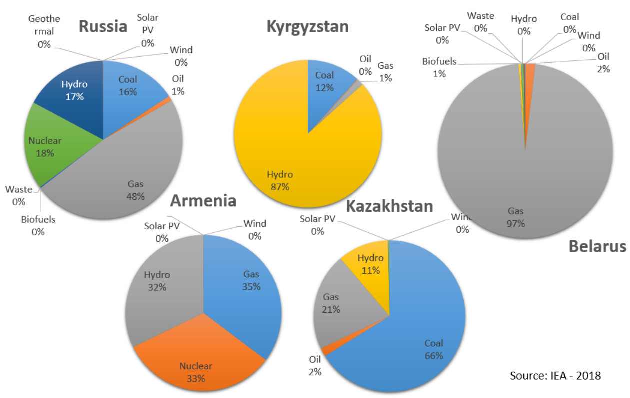

Fig. 4. EEU map with generation and consumption nodes

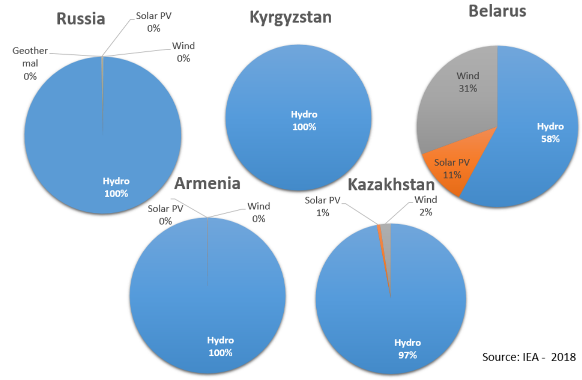

Fig. 5. EEU map with generation and consumption nodes

RU2 are the western part of Russia and Siberia respectively. KA1 and KA2 are North-Eastern and Southern Kazakhstan respectively. ARM, BEL and KYR represent Armenia, Belarus and Kyrgyzstan respectively. Maximum capacity is taken as 2500MW which is the standard for AC lines. If it were to be DC lines, we could go as high as 6400MW for the transmission lines.

-	D (km)	E. C. (MW)	Max C. (MW)
RU1 - RU2	3497	2000	3000
RU1 - BEL	717	1500	3000
RU1 - ARM	1826	0	1500
RU1 - KA1	2735	1170	2000
RU2 - BEL	4131	0	1000
RU2 - KA1	2015	2070	3000
KA1 - KA2	1264	1350	2500
KA1 - KYR	1241	0	1000
KA2 - KYR	400	2340	3000
BEL - ARM	2018	0	1500

VI. Results and Discussion

Two major case studies are presented here. The first is the case where the load is scaled for the end of the 10-year planning period and the second is the year-by-year solution approach.

A. End of 10-year Planning Period

It is good to note here that generation expansion was not considered. Rather cost of generation was chosen as a part of the objective. This, the authors did because of the current conditions in the countries present in the EEU. Especially the case of Russia which has a load factor of 70%. This basically implies that there are quite a good number of redundant generators for a country that has generation capacity of over 250GW. Thus, successful inter-connectivity with other countries and hence, greater transmission of its available generation might also discourage other countries from making generation investments, at least presently.

In another exciting analysis, examining the past five to ten years of electricity consumption of the EEU countries, Russia, Armenia and Kazakhstan exhibited a sustained and predictive growth in demand. However, the two other countries (Belarus and Kyrgyzstan) had unclear demand profiles which does not allow to make an informed 10-year prediction. For example, factors like economic and political turbulence have direct affects on electricity consumption. But, taking into account the establishment of the EEU in 2014 and the economic and power grid relations between the countries, as well as Russia being the biggest consumption hub by far, it seems prudent to take the growth in demand of Russia as the indicator for the EEUs overall growth.

Thus, Looking at the past 10 years of electricity demand in Russia an 11% increase in demand is expected for the next 10-year period. This value was utilized in scaling the overall consumption for the 10-year planning horizon. The results obtained are summarized below.

- No generation investment
- All lines were constructed. The authors think a good reason for this might be due of Armenia which has 2 interconnecting lines that were not built before connected to it from other countries (Out of 4 new proposed lines). This is essential also to enable seamless transfer of power from the adjoining nodes connected to Armenia. It is also important to mention that Armenia is the second smallest node in terms of generation and consumption. Thus, it was simply inevitable for the two lines connected to it to be built as this will ensure appropriate power transfer

balance.

- The power transfer are shown with arrows in figure 6

Fig. 6. Transmission Lines Power Flows

- The total transmission cost was $5.2 billion at the end of the planning period

B. Year-by-Year Planning

For this case, we essentially used the ideas itemized in IV. Interesting factors to note here:

- There was no looking ahead to see what the future cost(s) of generation or transmission might be
- There was nothing to check the increase of consumption for the coming year
- The result of the current run of the model is updated on the data before the next run is done

The solution returned constructing a line occasionally after the model is run for a year. At other times, the solution was simply to increase the flow on an existing line.

- In the first year, there was construction of the line connecting Western Russia to Armenia. This seemed to be a reasonable decision because Armenia is the only country in the coalition without a connection to any of the other 4 EEU countries.The transmission investment cost was $314 million at the end of the first year
- In the third year, Belarus to Armenia transmission connection was created to complete the power balance loop and ensure a better power flow across the member states.
- The progressing years witnessed increase in power flow as consumption increased
- In the 6th year, the line connecting Western Russia to North-Eastern Kazakhstan was built. The existing line was connecting North-eastern Kazakhstan to Siberia.

VII. Conclusion

The creation of a united energy market for the EEU faces many challenges regarding national power sector reform and cross-country policy. But given the existence of a regulatory framework that allows for the existence of a common energy market, it would be hugely beneficial for all parties to increase the already existing interconnection levels. The scale of the expansion process will require a large scale cooperation between not just the five EEU state, but the neighboring countries as well.

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