Dynamic Multi Sector Energy Economic Model for Sustainable Development in The Electricity Sector Of Bangladesh

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1.1 Introduction: Objective

The primary objective this research is to investigate the energy-economic relationships in the developing regions of South-Asia - Bangladesh to analyze different policy scenarios for sustainable development in the Electricity sector.

Fig. 1: 3E+S concept
1.2 Bangladesh: Country Facts and Figures

About Bangladesh

Independence: 1971
Land area: ~ 147,570 sq. km
Population: ~167.6 million (2020)
Population Density: 1120 per sq. km
GDP: 302.6 billion USD (2019)
GDP Growth Rate: 8.2% (2019)
GNI per-capita: 1827 USD (2019)

* In February 16, 2021 Bangladesh was recommended for graduation from LDC by UN Committee for Development Policy (CDC)
1.3 Bangladesh: the Developing Economy

Fig. 3: Bangladesh GDP and Growth [1]

Gross national income (GNI) per capita*

- **Value:** $1,827
- **Thresholds:**
  - Inclusion: $1,018 or below
  - Graduation: $1,222 or above
  - Income-only: $2,444 or above

Human assets index (HAI)*

- **Value:** 75.3
- **Thresholds:**
  - Inclusion: 62.0 or below
  - Graduation: 66.0 or above

Economic and environmental vulnerability index (EVI)*

- **Value:** 27.2
- **Thresholds:**
  - Inclusion: 36.0 or above
  - Graduation: 32.0 or below

Fig. 4: LDC Graduation Performance Review [2]
1.4 Energy Sector in Bangladesh

Fig. 5: Energy Balance of Bangladesh in 2019 [3,4]

Fig. 6: Energy Import and Self Sufficiency [4]
1.5 Depleting Natural Resource

Fig. 7: Historical Natural Gas Production and LNG Import [4]

Fig. 8: Natural Gas Reserve and Production Forecast [5]
1.6 Electricity Sector in Bangladesh

Fig. 9: Historical Electricity Demand and Projected Growth [6]

Fig. 6: Installed Capacity and Generation Mix in 2019-20[4]
1.7 CO₂ Emissions in Bangladesh

Fig. 11: Historical CO₂ Emission by Fuel[7]

Fig. 12: Historical CO₂ Emission by Sectors[7]
2.1 Dynamic Multi-Sector Energy Economic Model

DMSEE uses a linear approximation method to calculate nonlinear utility functions and production functions using linear programming. To consider substitution of goods, CES (Constant Elasticity of Substitution) type utility and production functions are considered.

General equilibrium data (input-output table, capital formation matrix, etc.)

Dynamic multi-sector energy economic model
Considering supply and demand balance of goods, capital, labor, etc. based on applied general equilibrium

Bottom-Up
Power sector model

Power supply, equipment construction

Production value of each industry, investment amount, consumption amount of each goods, power generation, power installed capacity composition, etc.

Fig. 13: Structure of DMSEE Model
2.2 DMSEE Model Structure

**Objective function:** Maximize \( \text{obj} = \sum_{r \in \mathbb{R}} \sum_{y=0}^{y-1} \sigma_{r,y} \left( \left( \text{util}_{H_{r,y}} + \text{util}_{g_{r,y}} \right) - \left( \text{tax}_{T_{r,y}} + \text{tax}_{B_{r,y}} \right) \right) \)

Subject to the constraints from both top-down (TD) and bottom-up (BU) sectors including:

**Top-Down (TD) Constraints:**
- Supply-demand balance,
- Physical / resource balance,
- Capital investment,
- Labor (population and skills),
- Linearization of CES function,

**Bottom-Up (BU) Constraints:**
- Technical limitations of each electricity technologies:
- Load following constrains of thermal power plants,
- Capacity factor of renewable generation technologies,
- Annual maintenance schedule,
- Capacity reserve & electricity supply-demand balance.
2.3 Single Region DMSEE Model for Bangladesh

Main features of the model:

- 8 aggregated economic sectors: AgL (Agriculture and Livestock), Coal, Oil, Gas, Ind (Industry), Tra (Transport), Ser (Service), Ely (Electricity)
- Single regions: Bangladesh (BGD)
- 6 time points, from 2025 to 2050 considering 2020 as base year
- Base year data for consumption and international trade has been obtained from GTAP 10 data-base.
- BU Electricity Sector has been subdivided into Nuclear, Coal, Oil, Gas, Hydro, Biomass, Solar PV and Wind power generation technologies.
2.4 Energy Resources Assumptions

Table: Reserves and Resources of Non-Renewable energy sources

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Unit</th>
<th>Reserves</th>
<th>Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(value)</td>
<td>EJ</td>
<td>Gt CO₂</td>
</tr>
<tr>
<td>Hard Coal</td>
<td>Giga ton coal eq. (Gtce)</td>
<td>624</td>
<td>18,288</td>
</tr>
<tr>
<td>Lignite</td>
<td></td>
<td>123</td>
<td>3,601</td>
</tr>
<tr>
<td>Coal (Total)</td>
<td></td>
<td><strong>747</strong></td>
<td><strong>21,889</strong></td>
</tr>
<tr>
<td>Conventional Crude Oil</td>
<td>Giga ton (Gt)</td>
<td>173</td>
<td>7,234</td>
</tr>
<tr>
<td>Shale Oil</td>
<td></td>
<td>2.2</td>
<td>91</td>
</tr>
<tr>
<td>Oil Sand</td>
<td></td>
<td>26</td>
<td>1,086</td>
</tr>
<tr>
<td>Extra Heavy Oil</td>
<td></td>
<td>42</td>
<td>1,752</td>
</tr>
<tr>
<td>Oil Shale</td>
<td></td>
<td>0.5</td>
<td>7.2</td>
</tr>
<tr>
<td>Oil (Total)</td>
<td></td>
<td><strong>243</strong></td>
<td><strong>10,070</strong></td>
</tr>
<tr>
<td>Conventional Natural Gas</td>
<td>Trillion Cubic Meter</td>
<td>191</td>
<td>7,261</td>
</tr>
<tr>
<td>Shale Gas</td>
<td></td>
<td>6.1</td>
<td>230</td>
</tr>
<tr>
<td>Tight Gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal-bed Methane</td>
<td></td>
<td>1.8</td>
<td>69</td>
</tr>
<tr>
<td>Aquifer Gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Hydrates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas (Total)</td>
<td></td>
<td><strong>199</strong></td>
<td><strong>7,560</strong></td>
</tr>
<tr>
<td>Fossil Fuel (Total)</td>
<td>EJ</td>
<td></td>
<td><strong>39,619</strong></td>
</tr>
<tr>
<td>Uranium</td>
<td>Million ton (Mt)</td>
<td></td>
<td><strong>1.2</strong></td>
</tr>
<tr>
<td>Thorium</td>
<td></td>
<td></td>
<td><strong>6.4</strong></td>
</tr>
<tr>
<td>Nuclear (Total)</td>
<td></td>
<td></td>
<td><strong>1.2</strong></td>
</tr>
<tr>
<td>Non-Renewable Fuels</td>
<td>EJ</td>
<td><strong>40,237</strong></td>
<td><strong>3,359</strong></td>
</tr>
</tbody>
</table>

Table: Energy Reserve Assumption [4, 8]

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>(Unit)</th>
<th>Global Reserve</th>
<th>Bangladesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>Giga ton coal eq. (Gt-coal eq.)</td>
<td><strong>747</strong></td>
<td><strong>0.293</strong></td>
</tr>
<tr>
<td>Oil</td>
<td>Giga ton oil eq (Gt-oil eq.)</td>
<td><strong>243</strong></td>
<td><strong>0.004</strong></td>
</tr>
<tr>
<td>Gas</td>
<td>Trillion cubic meter (Tcm)</td>
<td><strong>199</strong></td>
<td><strong>0.186</strong></td>
</tr>
<tr>
<td>Fossil Fuel</td>
<td>Exa-Joule (EJ)</td>
<td><strong>39,619</strong></td>
<td><strong>15.817</strong></td>
</tr>
</tbody>
</table>
2.4 Labor and Population Assumptions

Fig. 14: Labor (15-64 years) and Population Projections [7]
3.1 Input: GTAP Database [8]

* PRIVEXP : PRIVate household EXPenditures
* GOVEXP : GOVernment EXPenditures
* SAVE : savings
* VOA : Value of Output at Agent’s prices
* VDGA : Value of Domestic Government purchases, evaluated at Agents’ prices
* VDPA : Value of Domestic Private household purchases, evaluated at Agents' prices,
* NETINV : investment
* VDFA : Value of Domestic Firm Purchases (intermediate inputs to other producers) evaluated at Agents’prices

* VXMD : Firm’s Exports
* VIFA : Firm’s Imports
* VIPA : Household Import
* VIGA : Government Import
* MTAX : Import Tax
* XTAX : Export Tax
3.2 Bi-Lateral Trade Information (2015)

**Export:** 37 Bln$

**Import:** 47 Bln$

- **Cotton**
  - Export: 47 Bln$
  - Import: 2.95%
  - Total: $46.8B

- **Cereals**
  - Export: 37 Bln$
  - Import: 4.73%
  - Total: $37.3B

- **Iron and steel**
  - Export: 2.56%
  - Import: 4.9%

- **Plastics and articles thereof**
  - Export: 10.5%
  - Import: 3.84%

- **Apparel and clothing accessories; not knitted or crocheted**
  - Export: 42%
  - Import: 41.6%
3.3 Scenario Development

3 Different Scenario Based on per-capita Annual Consumption Growth:
- Low Growth (LG): average per-capita annual consumption growth 3.5%
- Business As Usual (BAU): average per-capita annual consumption growth 5.5%
- High Growth (HG): average per-capita annual consumption growth 7.5%

2 Different Scenario Based on CO₂ emission:
- No Carbon Restriction (BAU)
- Restrict CO₂ emission by 50%
4.1 Results: GDP Growth and Composition

Figure 15: GDP Composition at (a) Low growth, (b) BAU growth and (c) High growth Scenarios
4.1 Results: Primary Energy Production and Import

Figure 16: Energy Production at BAU case

Figure 17: Energy Import at BAU case
4.2 Results: Electricity Generation Mix

Figure 18: Electricity Generation Mix at (a) Low, (b) BAU and (c) High growth Scenarios
4.3 Results: Effect of Carbon Emission Restriction

- Solar PV comes into the electricity mix (17%) reducing the contribution of natural gas.
- Contribution from nuclear increases due to low carbon intensity.
- There is a small but negative effect on the GDP and electricity growth.
- Imposing carbon-tax might have negative impact on the economy, however it brings environmental sustainability by reducing CO2 emissions.

Figure 19: Generation-mix at BAU with 50% CO2 reduction w.r.t. BAU case
5. Conclusion & Future Work

- The DMSEE model relates the growth in electricity sector endogenously with the changes in other economic sectors.
- It also identifies the effect of policy change like carbon emission reduction policies and provides pathways to introduce renewables at larger scale.
- CO₂ emission restrictions could introduce large scale inclusion of solar PV and nuclear power in the electricity generation mix.
- Impact on material and industry sector could be linked with energy and electricity growth.
- The single country model could be expanded into multiple regions including nearby India, Nepal, Bhutan and Myanmar to observe the effect on electricity trade.
6. References

Thank You

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Appendix: DMSEE Methodology

CES function optimization for CGE model: The general form of CES function is given by

\[ Y = \left( \sum_i b_i x_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \]

where, \( Y \): production function or utility function, \( i \): number of goods, \( b_i \): input coefficient of good \( i \), \( x_i \): input quantity of good \( i \), \( \sigma \): elasticity of substitution.

As CES function is generally nonlinear and linear programming methods cannot be used to solve a programming problem having nonlinear constraints. Therefore, linearity is achieved by approximation of a linear function by the value of the substitute elasticity as shown below.

\[
Y = \min\{x_1, x_2, ..., x_i, ...\} \quad \text{if } \sigma \to 0 \quad \text{(Leontief type)}
\]

\[
Y = \left( \prod_i x_i^{\sigma} \right)^{\frac{1}{\sigma}} \quad \text{if } \sigma \to 1 \quad \text{(Cobb-Douglas type)}
\]

\[
Y = \sum_i b_i x_i \quad \text{if } \sigma \to \infty \quad \text{(Linear type)}
\]
Appendix: DMSEE Methodology (contd.)

DMSEE Model Constraints formulation:

- Balance of demand and supply (considering investment and trade):

\[
\begin{align*}
& h_{m,r,t} + g_{m,r,t} + \sum_{n=1}^{N} (a_{m,n,r} z f_{n,r,t} + c_{m,n,r} i_{n,r,t}) = x_{n,r,t} + \sum_{s=1}^{S} t r_{n,r,s,t} \\
& \sum_{y} x p_{q,y} \leq \sum_{q} D_{q,y}
\end{align*}
\]

- Constraint of exhaustible resources:

\[
\begin{align*}
& \sum_{y} x p_{q,y} \leq \sum_{q} D_{q,y}
& \beta_{a,r,t} \cdot Y_{a,r,t} \leq A_{a,r,t}
\end{align*}
\]
Appendix: DMSEE Methodology (contd.)

- Capital Investment: Each activity increases the depreciation of equipment by investment and enhances the production capacity. So, production is restricted by installed capacity in BU sectors.

\[ k_{B_t} = k_{B_0} + \sum_{i=0}^{I} F_{B_i} \eta_{I_i} i_{B_i} \]

where, \( k_B \): installed capacity, \( F \): investment matrix, \( \eta \): construction cost

- Labor and Production: Production requires labor as well as equipment. The labor force is measured in terms of population growth efficiency factors. The labor force at a particular time is related with the previous time point as shown in the following equation:

\[ l_{t+1} = (1 + \zeta) e_t (1 + \theta) l_t \approx (1 + \zeta + \theta) l_t = (1 + \gamma) l_t \]

where, \( l \): labor force, \( l' \): number of labors, \( e \): efficiency of labor, \( \theta \): population growth rate,
\( \zeta \): technology progress rate, \( \gamma = \theta + \zeta \)
• Physical quantity balance: The production amount should be equal to goods consumed and exported
\[ xp_{n,m,y} = xd_{m,y} + xex_{m,y} \]

• Capital investment for equipment: Considering the limited lifespan of equipment and depreciation, capital investment is required
\[ xe_{n,y,capital} = \sum_{y2}^{y} F_{n,y2} \eta_{l,n,y} x_{i,n,y2} + \delta_{n,y}XE0_{n,y,capital} \]

* Variable renewable generation: By utilizing capacity factor for each time point, renewable electricity generation is limited.
\[ xe_{n,y} \cdot CF_{n,s,t} = \eta_{K,n,y} \cdot xpS_{Bely,s,t,y} \]

* Electricity supply (spinning) reserve constraint: (for thermal power plants only)
\[ \sum_{n\in ELYS} xe_{n,t} \geq (1 + 0.05) \sum_{n\in ELYS} \eta_{K,n,t} \cdot MAXLOAD_{n,t} \]
### Appendix: DMSEE Methodology (contd.)

#### Table A1: Assumptions for Thermal Power Generation

<table>
<thead>
<tr>
<th></th>
<th>Nuclear</th>
<th>Coal</th>
<th>Oil</th>
<th>Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial capacity [GW]</td>
<td>0.0</td>
<td>1.5</td>
<td>6.5</td>
<td>12</td>
</tr>
<tr>
<td>Construction cost [$/kW]</td>
<td>4,000</td>
<td>2,700</td>
<td>2,000</td>
<td>1,600</td>
</tr>
<tr>
<td>Annual Average Availability [%]</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Seasonal Peak Availability [%]</td>
<td>20–90</td>
<td>90</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>Maximum Increase Rate of Output [1/h]</td>
<td>0.02</td>
<td>0.26</td>
<td>0.44</td>
<td>0.44</td>
</tr>
<tr>
<td>Minimum Increase Rate of Output [1/h]</td>
<td>0.02</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td>Life Time [year]</td>
<td>60</td>
<td>40</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Share of Daily Start and Stop</td>
<td>0.8</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

#### Table A2: Assumptions for Renewable Power Generation

<table>
<thead>
<tr>
<th></th>
<th>Hydro</th>
<th>Solar PV</th>
<th>Wind</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial capacity [GW]</td>
<td>0.25</td>
<td>0.5</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Construction cost [$/kW]</td>
<td>6,500</td>
<td>2,500</td>
<td>3,000</td>
<td>8,000</td>
</tr>
<tr>
<td>Annual Average Availability [%]</td>
<td>65</td>
<td>-</td>
<td>-</td>
<td>70</td>
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<tr>
<td>Maximum Increase Rate of Output [1/h]</td>
<td>0.05</td>
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<td>-</td>
<td>0.05</td>
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<tr>
<td>Minimum Increase Rate of Output [1/h]</td>
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<td>-</td>
<td>-</td>
<td>0.05</td>
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<tr>
<td>Life Time [year]</td>
<td>60</td>
<td>20</td>
<td>30</td>
<td>40</td>
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</table>
The End