Dynamic Transition Analysis With The Integrated Markal-EFOM System (TIMES)

International Institute for Carbon-Neutral Energy Research (I^2CNER) Project Report

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1 Introduction

We initiated a project in January 2018 to simulate dynamic transition scenarios for the energy industry in Japan to suggest pathways for minimizing carbon emissions. This report is a summary of the progress we have made so far, the challenges we currently face, and the future direction of this research.

2 Progress Summary

The tasks that we performed can be divided into two categories: technical tasks associated with implementation of details and features in our model, and data collection and organization. Our accomplishments have been:

2.1 Installation of and familiarization with VEDA (January – March 2018)

To model Japan's energy industry, we chose VEDA, a TIMES [1,2] shell. Using the simplest VEDA input files from the VEDA tutorial [2] as a starting point, we developed our own model files, which we have been progressively refining since then.

At the same time, we collected data pertaining to electricity generation and carbon emissions.

2.2 Incorporation of fossil fuel-related data(April – May 2018)

We incorporated data for electricity generation from fossil fuels from the Energy and Data Modelling Center (EDMC) databank [3], along with creating a simplified demand process reflecting recent trends in electricity demand in Japan.

While collecting these data, we noticed that the EDMC databank that we have been relying on has no data for the amount of electricity generated from individual fossil fuels for the years 2011-12. Instead, the amount of electricity generated from coal, oil, and natural gas is lumped together in one category entitled "thermal". Further, the 2016 data seem slightly inconsistent across different data tables in the EDMC databank. The source of variation in these numbers is likely to be the changes in the electricity distribution system of Japan since 2016.

2.3 Incorporation of nuclear, hydropower and renewables into the model(June – August 2018)

The process of incorporating these into the model was similar to that for previously mentioned energy sources but simpler, since the data obtained for these energy sources from EDMC were consistent across EDMC data tables and secondary sources [3–5]. We have also included processes for the projected growth of nuclear, solar and wind based on data from various studies, reports and articles. [6–11]

2.4 Refining CO_2 emission processes(August – September 2018)

While we had been modelling CO_2 emission processes in parallel with the electricity generation processes, it was only after incorporating all conventional energy sources that we could move on to aligning the model's CO_2 emission values with actual emissions from Japan. The major obstacle we faced was the absence of data pertaining to electricity generation from individual fossil fuels, with each fossil fuel's energy cycle having different emission coefficients. We estimated the missing figures based on previous years' trends [3, 12] and obtained reasonable approximations of electricity generation (see fig. 1), which result in CO_2 emission values that differ from actual values by about 5% at most (see fig. 2 and 3).

2.5 October 2018 – January 2019

2.5.1 Changing simulation timeframe to 2013-2100

As discussed previously, it became impossible to find exact data for fossil fuels for the years 2010,2011 and 2012. Hence the total CO_2 emissions for those years were very slightly off the mark. We sidestepped this problem by changing the initial year to 2013, for which we have exact data from EDMC [3].

2.5.2 Incorporation of the Contribution to Peak (PEAK) factor [2] factor

This parameter is defined as the fraction of a resource's installed capacity that is guaranteed to be available during peak demand. This introduces a notion of an energy resource's reliability. Its incorporation reduced excessive deployment of wind and solar. However, the PEAK factor values in the model [13] neglect the daily or seasonal variation of wind and solar, as the factor is annually averaged.

2.5.3 Basic Carbon Capture and Sequestration (CCS) Implementation

Some CCS data [13] were incorporated into one of the models. However, no CCS gets deployed in our models. We believe it should be deployed for an intermediate time-period, since in the absence of nuclear, only CCS can provide reliable, clean energy in conjunction with renewables. We have identified a few shortcomings in our model, some of which contribute to this problem:

Large amounts of offshore wind can be deployed: While we were initially reluctant to hard-code strict installed capacity limits into our model, we have since realized that Japan's underdeveloped offshore wind industry will not reach its full potential for a very long time, as offshore wind is extremely expensive to deploy in Japan. This is due to the unusually deep seabed that is very close to the Japanese coast. Japan Wind Power Association (JWPA) projections [9] are already ambitious, and our models should be closely aligned with them.

Wind and solar's daily and seasonal variance neglected: Their capacity factor is annually averaged. Their installed capacity should be matched by electricity storage or natural gas. Possible ways to implement this are discussed later.

We may be overestimating CCS costs: The costs associated with CCS for Japan have been hard to find as Japan, instead of building CCS pipelines like the US or China, intends to build a shipping network for offshore storage of captured and compressed CO_2. While this would make CCS plants more expensive in Japan, we cannot arrive at an exact figure. Based on our interaction with our Energy Analysis Division colleagues at Kyushu university, the costs of this are still being explored by the Japanese government.

2.6 February 2019 – April 2019:

2.6.1 Gradual collection and replacement of Levelized Cost of Electricity (LCOE) data with accurate cost structure

The results presented at the I^2CNER Annual Energy Analysis Division (EAD) workshop [14] were based entirely on LCOE analysis, as LCOE data and projections were readily available. However, it is more suitable to incorporate cost data in the recommended TIMES format, that is with the investment/capital cost, and fixed and variable operation and maintenance (O&M) costs. We believe that when there is no investment cost associated with an energy source, the deployment or premature retirement has no cost-penalty. This may cause resource deployments for unrealistically brief periods (see fig. 5).

2.6.2 Incorporation of semi-discrete investment sizes

Discrete investment sizes were incorporated in most scenarios' Discrete Investment (DSCINV) files [2], whereas the slightly improved semi-discrete installed capacity sizes are incorporated in the conventional-no-nuclear model (see Table 2). It is desired that all DSCINV files in the remaining three models include a similar semi-discrete installed capacity installation structure, as this helps eliminate the production-exceeding-demand bug (see fig. 4 and fig. 5).

3 Model description

The objective function [1] for the simulation is the system cost, and the primary constraints are the demand and the limit on CO_2 emissions based on I^2CNER goals. Hence, the simulations determine the energy mix most economically optimal for meeting Japan's future energy needs, when constrained by I^2CNER CO_2 emissions.

3.1 Key Simulation Parameters

The models include some combination of the technologies mentioned in Table 1; the exact combination for each model is described in Table 2.

Table 1: Main simulation parameters and features.

Start year	2013
End Year	2100
Demand increase rate	+1.7% p.a. [11]
Conventional sources	Coal, Oil, Natural Gas, Combined Cycle, Nuclear
Renewables	Solar, Wind, Geothermal, Hydro
Novel tech.	H_2(photocatalytic), CCS (point-capture)

Table 2: Model description.

Model Name	**Conventional technology**	**Novel technology**	**New nuclear reactors**
conv-free	✓	✗	✓
conv-nonuc	✓	✗	✗
i2cner-free	✓	✓	✓
i2cner-nonuc	✓	✓	✗

3.2 Assumptions

Our model focuses on the electricity generation sector. The following assumptions and limitations are present in our model:

1. All the energy generated by a given process is transferred to the grid without losses. Since the EDMC data have units of electrical energy produced (GWh), we have no need of incorporating data about raw fossil fuel consumption, plant efficiency, and utilization factors for the initially deployed electricity generation sources.

2. LCOE for fossil fuels and nuclear has been held constant throughout the simulation [4, 15, 16]. LCOE projections for wind and solar have been incorporated [16].

3. Oil-based electricity is retired relatively quickly, and new oil-based electricity deployment is disabled, due to the emphasis of the Japanese government on energy self-sufficiency and minimizing costs, and due to a general trend in the EDMC data [3] indicating declining use of oil.

4. Nuclear installed capacity is increased in chunks equivalent to the installed capacity of GE-Hitachi's Advanced Boiling Water Reactors (ABWR) [17], which are under consideration for construction [11].

5. Solar – Any new solar installed capacity created by the model has been assumed to be non-tracking type.

6. Hydropower – held constant at current levels.

7. Geothermal is expanded to its maximum potential [8].

8. The CO_2 emission constraints implemented are representative of I^2CNER goals of an 80% reduction in emissions from 1990 levels.

3.3 Model Data

Emission coefficients [11]: The emission coefficients are listed in Table 3. The data are in gCO_2/kWh. Hence, nuclear, solar and wind emissions from construction are averaged over the lifetime of the generation facility.

Table 3: List of emission coefficients used in the model.

Electricity source	**Emissions coefficient**
Coal	943
Natural Gas	599
Oil	738
Solar	38
Wind	25
Nuclear	21
Geothermal	13
Hydropower	11

LCOE [16] : LCOE data are appropriate for use in processes in which a fixed amount of installed capacity has already been deployed, i.e. the initial installed capacity, and where only the relative cost is important. The LCOE data (in million USD/GWh) are listed in Table 4.

Table 4: LCOE data used in the simulation.

Electricity source	**LCOE**
Coal	0.06
Natural Gas	0.08
Oil	0.39
Solar	0.161
Wind	0.144
Nuclear	0.1
Geothermal	0(fixed installed capacity)
Hydropower	0 (fixed installed capacity)

Detailed costs [18] : While the models with conventional energy sources have part of the cost structure listed in Table 5, these somewhat inaccurate and highly idealized figures need to be revised based on the data in the Advanced Reactors and Fuel Cycles (ARFC) I^2CNER repository, especially for offshore and onshore wind(current data are for the US from the Energy Information Administration (EIA) [18]), and for nuclear (to take construction delays into account).

Table 5: Detailed cost structure incorporated in some models.

Electricity source	Investment Cost (MUSD/GWh)	Fixed O&M Cost (MUSD/GW)	Variable O&M Cost (MUSD/GWh)
Coal	3784	51.39	0.0072
Combined Cycle	794	10.3	0.0021
Solar	1783	22.46	0
Onshore Wind	2773	40.85	0
Offshore Wind	8380	80.14	0
Nuclear	1600	0.0165	0.00933

Miscellaneous VEDA Parameters [2, 13]: The remaining TIMES parameters used in the models are listed in Table 6.

Table 6: Miscellaneous simulation parameters.

Electricity source	Efficiency	Utilization Factor	Lifetime (y)	PEAK factor
Coal	0.6	0.95	60	1.0
Combined Cycle	0.5	0.95	60	1.0
Solar	0.20-0.27	0.13	20-25	0.42
Onshore Wind	0.9	0.23-0.25	25	0.20
Offshore Wind	0.9	0.31-0.32	25	0.20
Nuclear	0.9	0.95	60	1.0

4 Results

Based on these assumptions and data(LCOE), the model yields the following results for the years 2011-16 (see figure 1), which are within 5% of the actual electricity generation figures obtained from EDMC. LCOE-based results for the entire time-period are present in the poster presented at the I^{2}CNER symposium [14].

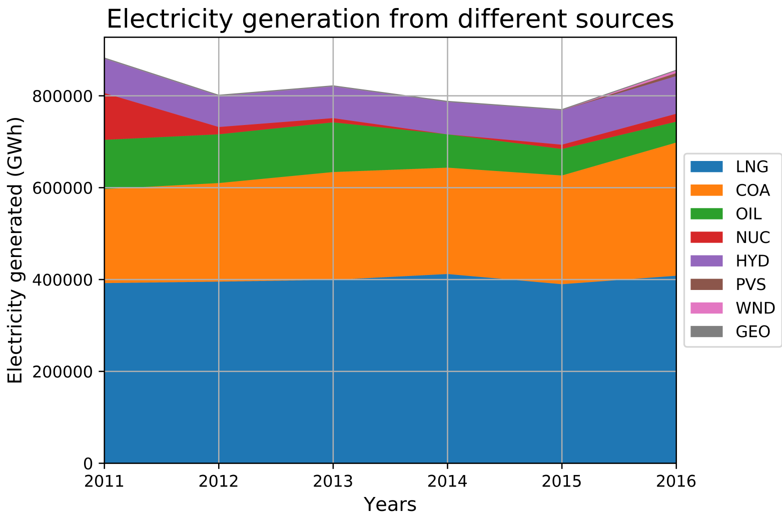

Figure 1: Electricity generation profile for the model's initial conditions.

The CO_2 emissions for the period 2011-16 are shown in figure 2. The maximum error is 5.7% (see figure 3), which is due to the aforementioned absence of accurate data for 2011, 2012 and 2016.

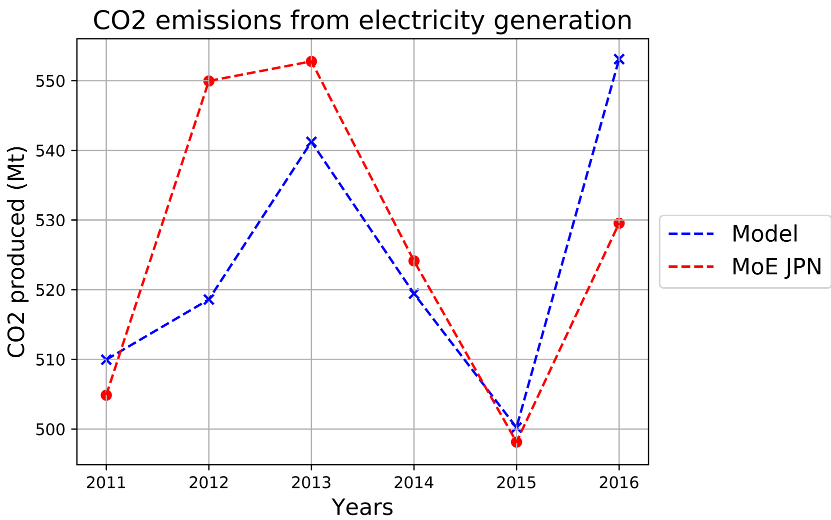

Figure 2: CO2 emissions from electricity generation compared with actual emissions reported by MOE, Japan

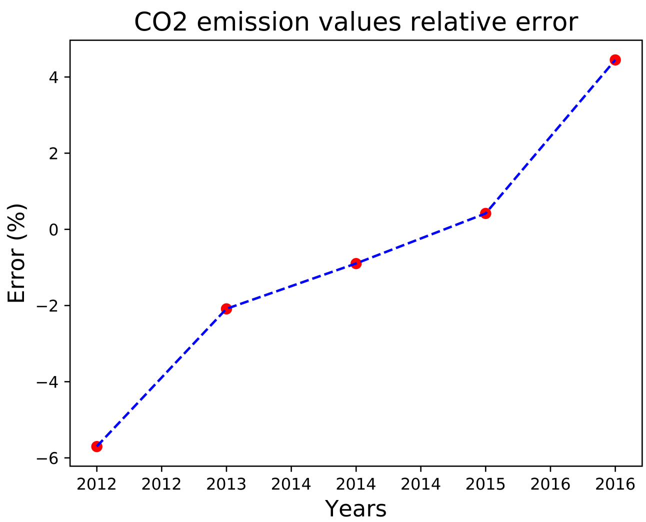

Figure 3: Relative error in CO2 emissions.

As mentioned previously, the importance of incorporating semi-discrete installed capacity investment intervals is demonstrated by figures 4 and 5. As seen in fig. 4, production exceeds demand if semi-discrete investment intervals are not used in DSCINV files. This issue is resolved if semi-discrete intervals are incorporated instead (see fig. 5).

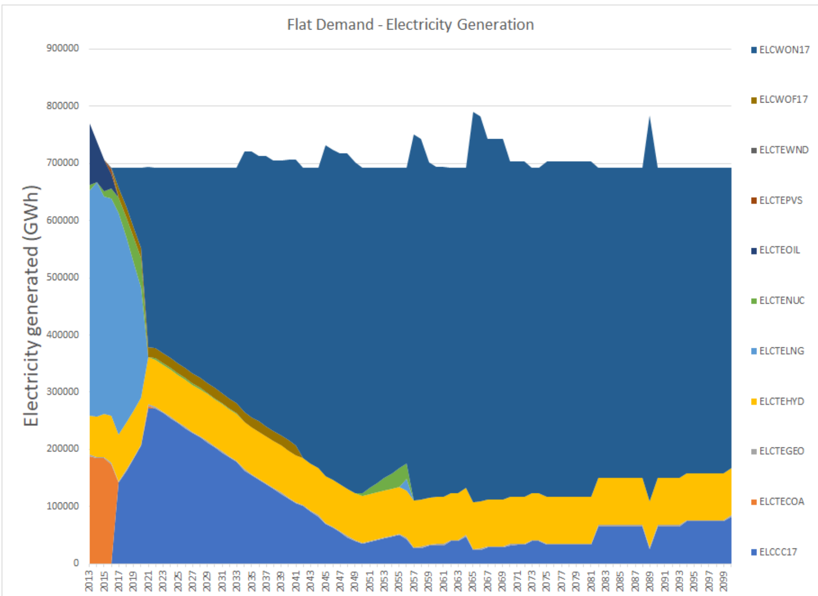

Figure 4: Erroneous results obtained with discrete investment sizes in DSCINV files.

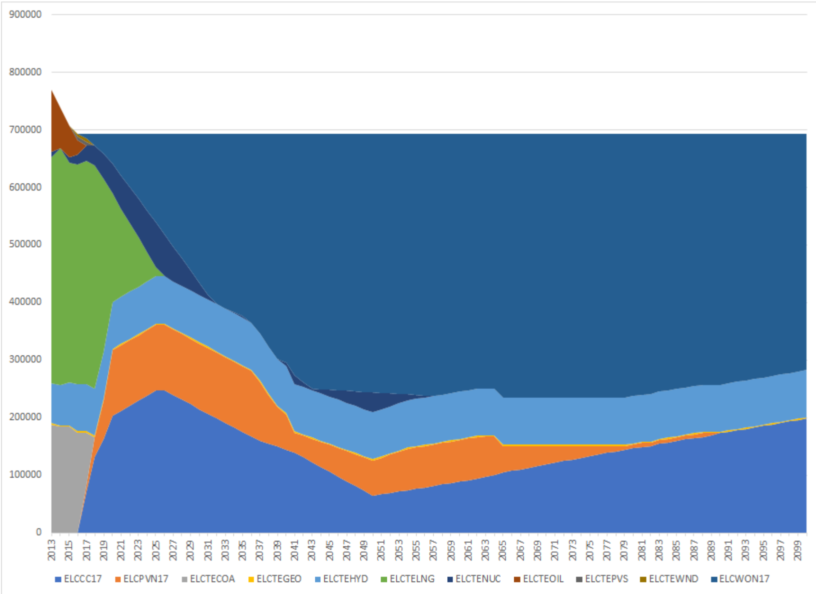

Figure 5: Accurate results obtained with semi-discrete investment sizes in DSCINV files.

4.1 Post Hoc Analysis and Challenges

The project has been delayed in part due to limited documentation and customer support available to VEDA users. The primitive, black-box like nature of the software inhibits efficient debugging. Therefore, while data acquisition and organization proceeded at the originally suggested pace, the incorporation of these data into the model has been behind schedule.

The EDMC is constantly being revised and updated, for both earlier (2010-2013) and later years(2016-). Hence, these data are often inconsistent or incomplete, and hence secondary sources must be used for verification.

5 Future Work

5.1 Next Steps

Remove pure oil based electricity generation from all models: We do not think Japan will ever increase its dependence on oil due to its cost, emissions intensity and due to the Japanese goal of increasing energy independence. Current trends support this assumption. While a few models already exclude oil-based energy, other models should also replace it with combined-cycle electricity generation for the sake of consistency.

Incorporate semi-discrete investment sizes: As stated previously, all DSCINV files must include semi-discrete installed capacity installation sizes for consistency.

Restrict maximum wind installed capacity: To align the model more closely with JWPA predictions [9], the maximum allowed capacities for wind should be reduced in the respective Maximum Capacity (MaxCAP) files.

Associate wind (and solar) with natural gas/storage: There may be three ways to accomplish this:

- **Define load curves for solar and wind:** This is the approach suggested by VEDA developers on their forum. However, the details for implementation of this particular approach are lacking in the TIMES/VEDA documentation. A successful implementation should incorporate the daily and seasonal variation of these electricity sources, and force the model to deploy natural gas or electricity storage to supplement wind and solar.
- **Replace annually averaged capacity factors and/or PEAK factors with seasonal (summer/winter) and diurnal (day/night) (i.e. SN,SD, WN, WD [2]) capacity factors** : The model may then automatically deploy natural gas to supplement wind and solar. If seasonal versions of these factors exist, this would be the easiest solution. TIMES Documentation Part II [1] may offer some insights in this regard.
- **Define a direct relationship between the capacities of wind and natural gas**:It might be possible to define a direct equation between the installed capacity of renewables and natural gas. Since no straightforward way to do this is described in the VEDA documentation [2], this would require utilization of the TIMES documentation [1], the VEDA attributes table, and possibly the assistance of the VEDA forum.

Cost Analysis - Some metric to compare the transition costs for each scenario should be calculated and presented with our results. For example, the LCOE for each scenario for different years (say 2030,2050,2100) could be calculated, or the total cost of the transition (investment+generation) could be juxtaposed for each scenario.

Incorporate more I^{2}CNER technology, such as perovskite solar cells, fuel cells for storage etc.

Sensitivity analysis: To identify optimum thresholds for costs or parameters (like efficiency) of novel technologies, especially I^{2}CNER technology, to maximize their efficacy and penetration.

5.2 Potential improvements

Revise CCS costs: Simplified CCS electricity generation processes exist in our I^{2}CNER models. These emit only 10% of the CO_2 that their corresponding fossil fuel technology emits [13]. In the model, these look like any other fossil fuel electricity generation process, except they are more expensive and have a significantly smaller emission coefficient. Such an implementation does **not** include retrofitting of CCS (i.e. adding point carbon capture capabilities to previously deployed fossil fuel plants). While we do not have Japan-specific data for CCS, we can use cost data from the US and do one of the following:

- Neglect the difference between Japan and the US, assuming that the government will foot the bill of setting up the CCS shipping network and offshore storage sites.
- Roughly increase the cost by a small percentage, since setting up the Japanese CCS shipping network and offshore storage sites will result in an increased cost per unit CO_2 captured and stored.
- Attempt to conduct a rough ab-initio analysis to find the cost of capturing, transporting and storing one ton of CO_2. The cost of capturing CO_2 is more or less uniform and readily available [13]. The cost of transport and storage can be estimated by finding the cost of offshore-drilling to the depths necessary for CO_2 storage, the cost of pressurizing 1 ton of CO_2, and the cost of transporting a ton of cargo to offshore storage sites by ship. The exact costs for this vary based on the scale of the operation.

Replace LCOE in all models with a detailed cost structure: All models must incorporate investment and O&M costs.

Incorporation of Japan-specific costs for wind: When incorporating JWPA predictions, it will be necessary to split off-shore wind into fixed and floating types. The cost data for this already exist in our repository thanks to Akari Minami, an undergraduate from Kyushu University who assisted with data collection and simulation during March 2019. These data need to be sifted through and incorporated into our model.

Revise nuclear costs: Current models include the ideal cost of nuclear, but actual costs are often higher due to delays in construction. This is accurately reflected in data from EIA [18], which already exists in our repository. This needs to be incorporated into our models to reduce over-deployment of nuclear.

Make electricity demand process more realistic: Demand should increase at +1.7 % per year until 2030 as per Ministry of Economy, Trade and Industry (METI) projections [11], and should plateau afterwards until 2100. More accurate data for 2030-2050 can be sought to further improve upon this, if possible.

Implement CCS retrofitting: The modelling process for this is somewhat complicated. CO_2 emitted from different fossil fuels would have to be tracked separately by creating TIMES CO_2 commodities for coal, oil and petroleum, to ensure that CO_2 from non-fossil fuel sources is not captured by the model. Next, the process that converts this CO_2 to captured CO_2 and atmospheric CO_2 would need to be defined. The total amount of CO_2 captured should be less than the total capacity of the CCS reservoirs around Japan [13].
The data for retrofitting in Japan are not easily available. Generic CCS data from other countries may be used if necessary.

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