**Derivation of Supply Curve of PV**

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# Supplementary Materials

# Note 1: Administrative divisions of South Korea.

- South Korea consists of a total of 17 provinces, each of which encompasses cities & counties, as indicated in the following table. In this paper, the administrative category at high-level is consistently referred to as 'province', while at low-level it is expressed as 'city & county'.

Table SM 1. Administrative divisions of South Korea

|  |  |  |  |
| --- | --- | --- | --- |
| Administrative category at high-level | | | At Low-level |
| Short name | Full name | Jurisdiction type | Number of city & counties |
| SU | Seoul | Special City | 25 counties |
| BS | Busan | Metropolitan City | 16 counties |
| DG | Daegu | Metropolitan City | 8 counties |
| IC | Incheon | Metropolitan City | 10 counties |
| GJ | Gwangju | Metropolitan City | 5 counties |
| DJ | Daejeon | Metropolitan City | 5 counties |
| US | Ulsan | Metropolitan City | 5 counties |
| SJ | Sejong | Special Autonomous City | 1 city |
| GG | Gyeonggi-do | Province | 31 city & counites |
| GW | Gangwon-do | Province | 18 city & counites |
| CB | Chungcheongbuk-do | Province | 11 city & counites |
| CN | Chungcheongnam-do | Province | 15 city & counites |
| JB | Jeollabuk-do | Province | 14 city & counites |
| JN | Jeollanam-do | Province | 22 city & counites |
| GB | Gyeongsangbuk-do | Province | 23 city & counites |
| GN | Gyeongsangnam-do | Province | 18 city & counites |
| JJ | Jeju | Special Self-Governing Province | 2 city & counites |

# A map of the country Description automatically generated

Figure SM 1. 17 Metropolitan cities & provinces in South Korea

# Note 2: GCAM-EML

- In the standard version of GCAM, there are two systems: the model engine (GCAM-core) and the model interface for querying scenario output. In contrast, GCAM-EML combines a model engine with a model interface. The model engine of GCAM-EML is written in C#, and the model interface is developed using Windows Presentation Foundation (WPF). The requirements for the GCAM-EML are as follows.

Table SM 2. Requirements for GCAM

|  |  |
| --- | --- |
| **Specification** | **Description** |
| Operating System | Windows 10 x64 |
| RAM | 32GB |

A screenshot of a computer

Description automatically generated

Figure SM 2. User interface of GCAM-EML

Table SM 3. Sources of data utilized in GCAM-EML

|  |  |  |  |
| --- | --- | --- | --- |
| Data | Year | Resolution | Source |
| Population | 2020-2070 | Nation | KOSIS (2023) |
| 2020-2050 | Province |
| 2020-2040 | City & County |
| 2040-2050 | City & County | Estimates |
| GRDP | 2020-2050 | Nation | OECD (2023) |
| 2020-2050 | City & County | Estimates |
| Energy balance | 2020 | Nation | KESIS (2023) |
| 2020 | City & County | KESIS (2023) |
| Power geneartion | 2020 | City & County (By plants) | EPSIS (2020) |
| Renewable generation | 2020 | City & County | KEPCO (internal) |
| Renewable capacity | 2020 | City & County | EPSIS (2020)  KEPCO (internal) |
| Renewable capacity factor | 2020 | City & County | KEPCO (internal) |
| ESS capacity factor | 2020 | Province | KPX (2023) |
| CHP generation | 2020 | City & County (By company) | KDHC (2023) |
| T&D loss factor | 2020 | City & County | KEPCO (2023) |
| Auxiliary use factor | 2020 | City & County | KEPCO (2023) |
| Nuclear generation plan | 2022-2036 | City & County (By plant) | MOTIE (2023) |
| Floor space | 2020 | City & County | MOLIT (2023) |
| Vehicle kilometer | 2020 | City & County | TS (2023) |
| Refining activity | 2020 | City & County (By company) | KPA (2023) |
| Location of steel manufacturer | 2020 | City & County (By company) | KOSA (2023) |
| Port cargo volume | 2020 | City & County (By port) | KITA (2023) |
| Airport passenger traffic | 2020 | City & County (By airport) | KCA (2023) |

# Note 2: Projection of population and GRDP at 229 citiy level

- (Population) Each province has projected its future population at the city level by 2040. To extend the data for the next ten years (2040-2050), the Auto-Regressive Integrated Moving Average (ARIMA) method has been applied. The augmented data is then converted to represent each city & county’s share of the national population over the entire period (2020-2050). The city & county’s population share is applied to the midpath of the national population by 2050. Ultimately, the future population pathways of all 229 city & counties are projected.

- (Estimation) The applied method for the population for 2040-2050 by 229 city & counties is described here. ARIMA is a widely used statistical method for time series forecasting. It's a flexible and powerful approach capable of capturing a variety of patterns present in time series data. Here is a breakdown of its components: Auto-Regressive (AR): This component models the relationship between an observation and a certain number of lagged observations (i.e., its own past values). It assumes that the current value of the series depends linearly on its previous values. Integrated (I) Term: This component represents the differencing of raw observations to make the series stationary (i.e., removing trends and seasonality). The number of differencing steps needed to achieve stationarity determines the order of integration (denoted by the "d" parameter). Moving Average (MA) Term: This component accounts for the relationship between the current observation and a linear combination of past white noise error terms. It helps capture the short-term fluctuations in the data that are not accounted for by the autoregressive component. ARIMA models are typically denoted as ARIMA(p, d, q), where, p is the order of the autoregressive term, d is the degree of differencing (order of integration), q is the order of the moving average term. Building an ARIMA model involves selecting appropriate values for these parameters based on the characteristics of the data, such as its trend, seasonality, and noise. This selection process often involves inspecting autocorrelation and partial autocorrelation plots, as well as performing statistical tests to ensure stationarity. Once the model is fitted to the data, it can be used for forecasting future values of the time series.

In this study, ARIMA models were fitted for each of the 229 cities & counties. The function (‘*auto.arima’*)from the R library (‘*forecast*’) was utilized to identify the best ARIMA model for each city & county. The *auto.arima* function returns best ARIMA model according to either the order of the autoregressive term (p), the degree of differencing (d) or the order of the moving average term (q) value (Hyndman and Khandakar, 2008; Wang et al., 2006)

- (GRDP) The GRDP for each of the 229 city &counties up to 2050 are assumed by multiplying the per capita GRDP for 2020 by the projected population pathways.

# Note 3: Electricity consumption of electric vehicle

- (Number of BEVs) The complete set of registered BEVs data is not universally accessible across all 229 cities & counties. Table SM 4 serves as a summary of the most comprehensive BEV data we were able to compile. This table includes information on provincial populations (KOSIS, 2023), the number of BEVs (KSGA, 2023), their proportions in South Korea, and the count of cities & counties within each province. The data on registered BEVs is sourced from various provinces and cities & counties. Provinces in Group A provide fully available data, encompassing cities & counties, time horizons, and vehicle type information. Group B provinces do not distinguish between vehicle types in their data. Group C provinces lack vehicle type information for the year 2020, even though they possess BEV data organized by cities & counties. In the case of Group D, GJ province, BEV data is available for three out of the five cities & counties, categorized by vehicle types in 2022, while the remaining two cities & counties lack any data. Group E provinces do not possess any BEV data at the city & county level. For provinces from Group B to E, missing BEV data was estimated as follows. Assumptions are made to estimate the number of registered BEVs in 2020 by cities & counties and vehicle type. Firstly, in cases where the number of EVs per city & county is unavailable for a given province, it is assumed that the distribution of total vehicles by city & county reflects the distribution of EVs across cities & counties. Secondly, in the absence of data for 2020, the growth rate of the total BEVs for the entire province is calculated from 2020 to the available data year. This growth rate is then applied to estimate the number of BEVs in 2020. Thirdly, if the data does not specify the number of BEVs by vehicle type and only provides the total count, the vehicle type distribution in the province for 2020 is uniformly applied to each city & county.

- (Vehicle Kilometer Traveled) Information on the annual VKT for BEVs is unavailable. Thus, this study assumes that drivers cover equivalent distances regardless of the fuel type of their vehicles. Figure SM 3 shows annual VKT per vehicle by cities & counties in 2020 by vehicle types (car, truck, and bus). Average annual VKT per car, truck, and bus are 12,815km, 16,962km, 19,312km respectively in 2020 (TS, 2023)

- (Energy Efficiency) The energy efficiency of BEVs was assumed to vary among vehicle types, while remaining consistent across municipalities. Representative models for BEV cars, trucks—Ioniq 5 (Hyundai), Porter II Electric (Hyundai—were selected based on sales figures. Their respective energy efficiencies are known to be 4.8 km/kWh, 3.1 km/kWh (Hyundai, 2023).

Table SM 4. BEV data status by regions

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Province** | **Specification in 2020** | | | **Raw Data dimension** | | | **Type of Estimation method** |
| **Population**  **(share, %)** | **Number of BEVs**  **(share, %)** | **Number of municipality** | **Spatial resolution** | **Time horizon** | **Vehicle type** |
| SU | 9,668  (18.7%) | 23,393  (17.3%) | 25 | 25 | 2020 | car, bus, truck | A |
| BS | 3,392  (6.5%) | 5,355  (4.0%) | 16 | 16 | 2020 | car, bus, truck | A |
| DG | 2,418  (4.7%) | 12,630  (9.4%) | 8 | 8 | 2020 | car, bus, truck | A |
| IC | 2,943  (5.7%) | 5,366  (4.0%) | 10 | 10 | 2020 | car, bus, truck | A |
| GJ | 1,450  (2.8%) | 3,210  (2.4%) | 5 | 3 | 2022 | total | D |
| DJ | 1,464  (2.8%) | 4,469  (3.3%) | 5 | 5 | 2021 | total | C |
| US | 1,136  (2.2%) | 2,274  (1.7%) | 5 |  |  |  | E |
| SJ | 356  (0.7%) | 1,148  (0.9%) | 1 | 1 | 2020 | car, bus, truck | A |
| GG | 13,427  (25.9%) | 20,477  (15.2%) | 31 | 31 | 2020 | car, bus, truck | A |
| GW | 1,543  (3.0%) | 4,078  (3.0%) | 18 |  |  |  | E |
| CB | 1,601  (3.1%) | 3,883  (2.9%) | 11 | 11 | 2020 | total | B |
| CN | 2,121  (4.1%) | 5,489  (4.1%) | 15 |  |  |  | E |
| JB | 1,804  (3.5%) | 3,323  (2.5%) | 14 | 14 | 2022 | total | C |
| JN | 1,852  (3.6%) | 5,223  (3.9%) | 22 | 22 | 2020 | car, bus, truck | A |
| GB | 2,639  (5.1%) | 7,051  (5.2%) | 23 |  |  |  | E |
| GN | 3,340  (6.4%) | 6,308  (4.7%) | 18 |  |  |  | E |
| JJ | 675  (1.3%) | 21,285  (15.8%) | 2 | 2 | 2022 | total | C |

A graph of a graph

Description automatically generated with medium confidence

Figure SM 3. Annual VKT per vehicle by municipalities in 2020, a)car, b) truck

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GW: <https://kosis.kr/statHtml/statHtml.do?orgId=211&tblId=DT_PBOOO1_32&conn_path=I2>

CB: <https://kosis.kr/statHtml/statHtml.do?orgId=212&tblId=DT_PBOOO1_33&conn_path=I2>

CN: <https://kosis.kr/statHtml/statHtml.do?orgId=213&tblId=DT_PBOOO1_34&conn_path=I2>

JB: <https://kosis.kr/statHtml/statHtml.do?orgId=214&tblId=DT_PBOOO1_35&conn_path=I2>

JN: <https://kosis.kr/statHtml/statHtml.do?orgId=215&tblId=DT_PBOOO1_36&conn_path=I2>

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