Technical Appendix

Electric Motors

1. Introduction

This appendix offers a detailed explanation of the specific assumptions used in the motor module of Mepsy. For information on outputs and data sources for the parameters, please refer to the comprehensive Mepsy Methodology document.

Mepsy's electric motors model covers motors used in the industrial sector, with a focus on medium and large-sized motors.

Medium-Size Motors (0.75 kW to 375 kW): These motors account for about 68% of electricity consumed by electric motors and are primarily used in appliances such as centrifugal pumps, compressors, fans, and various industrial handling and processing tasks.

Large Motors (375 kW to 100,000 kW): These are high-voltage polyphase motors, often designed for custom industrial appliances. Operating at voltages between 1 kV and 20 kV, they are usually synchronous motors, assembled on-site. While they account for only about 0.03% of the total stock of electric motors, large motors represent roughly 23% of total energy consumption. They are often used in heavy industrial and infrastructural operations.

2. Shipments and Stock

CLASP purchased market data from Omdia, including the sales for centrifugal pumps, compressors, and industrial fans from 2018 to 2023. For countries with missing sales data, we estimated motor sales by applying their 2020 Gross Domestic Product (GDP) share relative to the regional GDP (where sales data is available). The compound annual growth rates (CAGR) from 2020 to 2023 were used to project motor sales up to 2030.

$$Motor\ Sales_i = \frac{GDP_i}{GDP_{region/country}} \times Motor\ Sales_{region/country}$$

Where:

$Motor\ Sales_i$ is the estimated motor sales for country i in 2020;

GDP_i is the Gross Domestic Product of country i in 2020;

$Motor\ Sales_{region}$ is the actual motor sales data available for the region or country.

Mepsy estimates the stock or number of motor in use in each country by accumulating shipments since 2005. Once shipped, motors enter service and remain in service until they fail beyond repair or are otherwise replaced. We used the Weibull Distribution function to model survival probabilities $P\ (x)$ of appliances and calculate the surviving stock of a certain year (y), based on the cumulative survival appliances from the previous year $(Stock(y-1))$.[1]

$$P\ (x) = e^{-\left(\frac{x-\theta}{\alpha}\right)^{\beta}}$$

Where:

$P\ (x)$ is the probability that the appliance is still in use at a certain age (x);

x is the appliance age;

α is the scale parameter, which corresponds to the decay length in an exponential distribution, also known as lifetime. In Mepsy, we set the lifetime of motor at 12.[2]

β is the shape parameter, which determines how the failure rate changes over time;

θ is the delay parameter, which introduces a delay before any failures occur.

Mepsy also refers to LBNL study to determine a shape parameter (β) of 1.2 and a delay parameter (θ) of 1.0.[2]

CLASP used regression analysis to forecast motor sales until 2050. Regression analysis is a statistical method that examines how changes in one or more independent variables are related to changes in the dependent variable. In this case, CLASP correlated motor sales (the dependent variable) with socio-economic factors (the independent or driver variables) for the same countries and the most recent year available. The results of this analysis were then used to project sales through to 2050. The formula is given by:

$$\begin{aligned} logit(\mu_c) = \beta_0 + \beta_1 \times GDP_{industry,c} \\ + \beta_2 \times Warehouse\ Building\ Stock_c + \beta_3 \\ \times\ Employment_{Industry,c} + \beta_4 \times Export\ Goods\ Value_c \end{aligned}$$

Where:

μ_c is the sales for the country (c) for motor;

β_0 is the intercept term;

$\beta_1, \beta_{2,}\beta_3$ are the coefficients for the respective independent variables;

[1] LBNL. Lutz et al. 2011. Using National Survey Data to Estimate Lifetimes of Residential Appliances. https://www.osti.gov/biblio/1182737

[2] "E_MR_Topmotors_Market_Report_2020.Pdf," accessed December 12, 2024, https://topmotors.ch/sites/default/files/2021-03/E_MR_Topmotors_Market_Report_2020.pdf.

$GDP_{industry,c}$ is the Gross Domestic Product at Purchasing Power Parity (GDP PPP in the country c;

$Warehouse\ Building\ Stock_c$ is the total building stock of warehouses in country c, $Employment_{Industry,c}$ is the percentage of the total workforce that is employed in industrial sectors;

$Export\ Goods\ Value_c$ is the total value (in US dollars) of exported goods in country c.

For motors, a regression analysis was used to project the sales. The results show a correlation between sales (dependent variables) and several socio-economic factors (driver variables), including Gross Domestic Product at Purchasing Power Parity (GDP PPP), warehouse building stock, employment in industry sector, and export goods/services measured in US dollars.[3,4] Due to the high variance of the motor sales value of different countries, CLASP divided 162 countries into four separate groups based on their sales numbers in 2019 to build different regression models. For countries with motor sales exceeding 600,000 units in 2019, the following equation was used:

$$Motor\ Sales = \left(-2.03 + 5.79\ \times 10^{-4} \times GDP_{industry,c} + (-1.73) \times 10^{-5} \times Warehouse\ Building\ Stock_c\ \right)$$

For countries with motor sales between 99,000 and 600,000 units in 2019, the following equation was used:

$$Motor\ Sales = \left(1.64 - 4.74\ \times 10^{-1} \times GDP_{industry,c} + (4.93) \times 10^{-11} \times Export\ Goods\ Value_c\ \right)$$

For countries with motor sales between 20,000 and 99,000units in 2019, the following equation was used:

$$Motor\ Sales = \left(3.23 + 0.19 \times GDP_{industry,c} - 7.47 \times Employment_{Industry,c} - 9.41 \times Warehouse\ Building\ Sotck_c + 2.5\ \times 10^{-11} \times Export\ Goods\ Value_c\right)$$

For countries with motor sales below 20,000 units in 2019, the following equation was used:

$$Motor\ Sales = \left(2.36 + 0.19 \times GDP_{industry,c}\ \right)$$

[3] "World Bank Open Data," World Bank Open Data, accessed January 16, 2025, https://data.worldbank.org.

[4] "Sign in to Your Account," accessed January 16, 2025, https://login.microsoftonline.com/4ee48f43-e15d-4f4a-ad55-d0990aac660e/saml2?client-request-id=d99ab87e-a5a7-4af2-996c-dcd887240443&sso_nonce=AwABEgEAAAADAOz_BQD0_3wX7UM9vmHb5_inX1p7gyKajzJQBFfM1gz7wmwQHYGh1s-n_WvSZ0aU5eTiexmBhPSalmWTIXicbqhG-_W0mvogAA&mscrid=d99ab87e-a5a7-4af2-996c-dcd887240443.

Based on the correlation, Mepsy fills the data gaps for the remaining countries. This relationship is then used to extrapolate sales through 2050, incorporating projected driven variables.[5] Additional details of this approach are provided in the 'Extending-Mepsy to 2050' paper.[6] For the period from 2050 to 2060, Mepsy extrapolates appliance sales based on the compound annual growth rate (CAGR) calculated from the data between 2045 and 2050.

REFINED MOTOR MARKET SIZE IN 2024

China: Due to data limitations, a top-down approach was used to refine the motor stock estimate in China. National industrial energy consumption data was collected and forecasted from 2005 to 2060. Motor energy consumption was assumed to account for 75% of the total electricity used.[6] From this, the motor stock was then calculated by dividing the total motor electricity consumption by the unit energy consumption (UEC).

India: Similar to China, a top-down approach was applied to estimate the motor stock in India. Annual industrial electricity consumption data was collected from the India Yearbook, published by the Ministry of Statistics and Programme Implementation (MoSPI).[7] Based on the growth projections provided by The Energy and Resources Institute, the industrial sector's future electricity consumption was forecasted.[8] Next, an assumption was made that 65% of the industrial electricity consumption was used by motors, allowing the calculation of the motor electricity consumption. Finally, using the motors Unit Energy Consumption (UEC), the motor stock from 2005 to 2060 was estimated.

United States: The US Department of Energy provides annual motor shipments by horsepower range from 2005 to 2060.[9] Shipments of industrial motors were calculated based on the distribution of industrial motors across each horsepower range (Figure 1).

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[5] In the model, we use linear interpolation to ensure data availability for the intervening years. A 100% cap was applied to electrification and urbanization, meaning the rate will not increase once it reaches 100%.

[6] "中国电机系统能效提升机制与政策研究项目-政策报告-Final.Pdf," accessed December 12, 2024, https://www.efchina.org/Attachments/Report/report-cip-20170622/%E4%B8%AD%E5%9B%BD%E7%94%B5%E6%9C%BA%E7%B3%BB%E7%BB%9F%E8%83%BD%E6%95%88%E6%8F%90%E5%8D%87%E6%9C%BA%E5%88%B6%E4%B8%8E%E6%94%BF%E7%AD%96%E7%A0%94%E7%A9%B6%E9%A1%B9%E7%9B%AE-%E6%94%BF%E7%AD%96%E6%8A%A5%E5%91%8A-Final.pdf.

[7] "Chapter-6.Xlsx," accessed December 12, 2024, https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fmospi.gov.in%2Fsites%2Fdefault%2Ffiles%2Fpublication_reports%2FEnergy_Statistics_2023%2FChapter-6.xlsx&wdOrigin=BROWSELINK.

[8] "Power_Sector_2050_0.Pdf," accessed December 12, 2024, https://teriin.org/sites/default/files/2024-02/Power_Sector_2050_0.pdf.

[9] "Regulations.Gov," accessed December 12, 2024, https://www.regulations.gov/document/EERE-2020-BT-STD-0007-0042.

FIGURE 1. DISTRIBUTION OF ELECTRIC MOTOR BY SECTOR BY HORSEPOWER RANGE

Equipment Class Group	Horsepower Range	Representative Unit (RU)	Industrial Sector (%)	Commercial Sector (%)	Agricultural Sector (%)
MEM 1-500hp, NEMA Design A & B	1 ≤ hp ≤ 5	1	47.2	52.8	0
	5 < hp ≤ 50	2	47.2	52.8	0
	50 < hp <100	3	71.7	21.3	7.0
	100 ≤ hp ≤ 250	4	82.2	14.8	3.0
	250 < hp ≤ 500	5	77.0	20.0	3.0
MEM 501-750hp, NEMA Design A & B	500 < hp ≤750	6	77.0	20.0	3.0
AO-MEM (Standard Frame Size)	1 ≤ hp ≤ 20	7	51.4	48.6	0
	20 < hp ≤ 50	8	51.4	48.6	0
	50 < hp < 100	9	51.4	48.6	0
	100 ≤ hp ≤ 250	10	51.4	48.6	0
AO-Polyphase (Specialized Frame Size)	1 ≤ hp ≤ 20	11	51.4	48.6	0

*May not sum to 100% due to rounding

EU-27: Eurostat provided annual motor production export and import data from 2005 to 2022.[10] We assumed 30% of total sales are industrial motors. The growth trend of the motor stock follows the industrial sector energy consumption trend reported by OECD Europe.[11]

3. Unit Energy Consumption, Usage, and Efficiency Scenarios

The unit energy consumption (UEC) of the electric motors for each country is calculated by combining the UEC values of the compressor, pump, and fans, with each value weighted based on their respective market share of total motor shipments. Additionally, the unit energy consumption of the different loads was divided by motor efficiency to obtain energy consumption of the entire system. Each motor component UEC was calculated as follows:

$$UEC_{compressor} = (Power_{Nameplate,Compressor} \times Load\ Factor_{ave.} \times Annual\ Operating\ Hours_{ave.} \div Efficiency\ Ratio)$$

$$UEC_{pump} = (Power_{Nameplate,\ Pump} \times Load\ Factor_{ave.} \times Annual\ Operating\ Hours_{ave.} \div Efficiency\ Ratio)$$

$$UEC_{fans} = (Power_{Nameplate,\ Fans} \times Load\ Factor_{ave.} \times Annual\ Operating\ Hours_{ave.} \div Efficiency\ Ratio)$$

[10] "Statistics | Eurostat," accessed December 12, 2024, https://ec.europa.eu/eurostat/databrowser/view/ds-056120__custom_11482793/default/table?lang=en.

[11] Ibid.

Where:

> $(Power_{Nameplate,\ Compressor}$ represents the average nameplate power of the motor component. Motors are typically defined by its rated capacity, also called nameplate power. However, most electric motors are designed to run at 50% to 100% of rated load. Maximum efficiency is usually near 75% of the rated load. The ratio between the actual operating power and the nameplate power is the average load factor ($Load\ Factor_{ave.}$).
>
> The Efficiency Ratio ($Efficiency\ Ratio$) reflects how efficiently the motor converts electrical energy into mechanical energy. If the efficiency is 80%, only 80% of the electrical energy is converted into useful work, while the remaining 20% is lost, often as heat. In the calculation, efficiency ratio is defined by a country's current Minimum Energy Performance Standards (MEPS) level, ranging from IE0 to IE4, and the product output, which is calculated from nameplate power and load factor. IE0 means that no MEPS requirements exist in the country. Each IE level corresponds to a specific efficiency ratio for different types of motor, as listed in IEC60034-30-1 in Table 2. Since the representative unit for MEPS is a 4-pole motor, the calculation uses the efficiency ratio specified for the 4-pole motor category.

The UEC of electric motor is then calculated as follows:

$$UEC_{Electric\ motor} = UEC_{compressor} \times \frac{Compressor\ Shipment}{Total\ motor\ Shipment} + UEC_{pump} \times \frac{Pump\ Shipment}{Total\ motor\ Shipment} + UEC_{fans} \times \frac{Fans\ Shipment}{Total\ motor\ Shipment}$$

Based on research, the model includes several assumptions for compressor, pump, and fans in Mepsy.

TABLE 1. MEPSY MAJOR ASSUMPTIONS FOR MOTOR AND THEIR REFERENCES

AVERAGE COMPRESSOR NAMEPLATE POWER (KW)	AVERAGE CENTRIFUGAL PUMP NAMEPLATE POWER (KW)	AVERAGE INDUSTRIAL FAN NAMEPLATE POWER (KW)	AVERAGE COMPRESSOR LOAD FACTOR (%)	AVERAGE CENTRIFUGAL PUMP LOAD FACTOR	AVERAGE CENTRIFUGAL PUMP LOAD FACTOR	AVERAGE COMPRESS OR USAGE (HR/YR)	AVERAGE CENTRIFUGAL PUMP USAGE (HR/YR)	AVERAGE INDUSTRIAL FAN USAGE (HR/YR)	AVERAGE COMPRESSOR LIFETIME (YR)	AVERAGE CENTRIFUGAL PUMP LIFETIME (YR)	AVERAGE INDUSTRIAL FAN LIFETIME (YR)
11.4	11.4	7.1	60	60	60	4500	4500	4500	12	12	12
Reference: "Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems," IEA Energy Papers, vol. 2011/07, IEA Energy Papers, May 1, 2011, https://doi.org/10.1787/5kgg52gb9gjd-en. Reference:						Reference: "E_MR_Topmotors_Market_Report_2020.Pdf," accessed December 12, 2024, https://topmotors.ch/sites/default/files/2021-03/E_MR_Topmotors_Market_Report_2020.pdf.					

The UEC values under the **Business-as-Usual** (BAU) scenario are directly calculated with the assumptions and the formulae outlined. The efficiency ratio will be different for each country based on their current MEPS requirement for motors and the product output power. For example, if a country has no MEPS for compressors, the model will apply an efficiency ratio based on IE0 level and an output of 6.84kW, which corresponds to an efficiency ratio of 81.6%.[12]

Global Benchmark scenario: For countries with no standards, the efficiency requirement for UEC was set at IE3, with efficiency ratios set at 89.6% for compressors and fans and 88.6% for pumps. For countries that have mandated IE3 as the efficiency level for motors, the UEC were set between the requirements for IE3 and IE4.

Net Zero Hero (NZH) scenario: UECs for all countries were set at 50% of the BAU value to align with the ambitious targets outlined in the Net Zero Heroes report.

TABLE 2. EFFICIENCY RATIO UNDER DIFFERENT IE LEVELS FOR 4 POLE MOTOR

OUTPUT	IE0	IE1	IE2	IE3	IE4
KW			4 POLE		
0.12	40	50	59.1	64.8	69.8
0.18	48.4	57	64.7	69.9	74.7
0.2	50.2	58.5	65.9	71.1	75.8
0.25	53.8	61.5	68.5	73.5	77.9
0.37	59.2	66	72.7	77.3	81.1
0.4	60.2	66.8	73.5	78	81.7
0.55	64	70	77.1	80.8	83.9
75	66.5	72.1	79.6	82.5	85.7
1.1	70	75	81.4	84.1	87.2
1.5	72.6	77.2	82.8	85.3	88.2
2.2	75.6	79.7	84.3	86.7	89.5
3	77.8	81.5	85.5	87.7	90.4
4	79.7	83.1	86.6	88.6	91.1
5.5	81.6	84.7	87.7	89.6	91.9
7.5	83.2	86	88.7	90.4	92.6
11	85.1	87.6	89.8	91.4	93.3
15	86.4	88.7	90.6	92.1	93.9
18.5	87.2	89.3	91.2	92.6	94.2
22	87.9	89.9	91.6	93	94.5
30	88.8	90.7	92.3	93.6	94.9
37	89.4	91.2	92.7	93.9	95.2
45	90	91.7	93.1	94.2	95.4
55	90.5	92.1	93.5	94.6	95.7
75	91.2	92.7	94	95	96
90	91.6	93	94.2	95.2	96.1

[12] The output of compressor is calculated by multiplying nameplate power 11.4 kw with the load factor (60%). The result is 6.84 kW, which falls between the 5.5 kW and 7.5 kW levels in the table. The model will select the efficiency ratio corresponding to the lower output level.

110	92	93.3	94.5	95.4	96.3
132	92.2	93.5	94.7	95.6	96.4
160	92.6	93.8	94.9	95.8	96.6
200	92.8	94	95.1	96	96.7
250	92.8	94	95.1	96	96.7
315	92.8	94	95.1	96	96.7
355	92.8	94	95.1	96	96.7
400	92.8	94	95.1	96	96.7
450	92.8	94	95.1	96	96.7
500	92.8	94	95.1	96	96.7

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