# Materials in Energy Systems Model – User Manual

This document is intended to guide future users of the dynamic material flow analysis model originally developed in Dirk Jacobs’ MSc thesis “The Disproportionality Problem: A Dynamic Material Flow Analysis of Raw Resource Disproportionality and Policy Interventions for Demand Reduction in the Netherlands”, which can be accessed at:

<https://repository.tudelft.nl/record/uuid:0ec6f504-6c3f-4f73-a6f0-3427651df760>

Since then, the model has been further developed by Dirk Jacobs and Bhuvesh Kaushik under the supervision of Benjamin Sprecher. The updated version introduces dynamic parametrisation for material intensities, technology lifetimes, technology market shares, and global supply. It also incorporates material recycling and includes historical installed capacities of the Dutch energy system from 2000 onwards.

The most up to date version of the underlying model can be accessed: <https://github.com/dirkjac99/EnergySystem-StockFlow>

This user manual consist of several sections:

* Theoretical Background
* How to use the model
* Addition of parameters
* Data interpretation
* Model limitations

## Theoretical Background

The model applies a Dynamic Material Flow Analysis (dMFA) approach, which estimates past and future flows and stocks to assess whether future resource demands can be met.

Historical datasets and scenarios provide the required and existing energy generation capacities for different technologies over time, referred to as installed capacities. Annual installed capacities are estimated through interpolation, producing a discrete time series known as the stock.

The MFA model is stock-driven: inflows (IN), outflows (OUT), and net additions to stock (NAS) are derived directly from stock levels.

The lifetime of a technology refers to the average number of years it remains in use and is represented as the mean of a normal distribution. The uncertainty of this estimate is captured by the standard deviation, which due to limited data, is set to one year for all technologies. Together, these parameters define the survival curve (surv()), which indicates the proportion of an inflow cohort remaining in stock after a given number of years, where F() denotes the cumulative distribution function.

Material flows ), inflow, outflow, and net additions to stock (NAS), are calculated by multiplying a technology’s installed capacity, material intensity, and market share. Material intensity (MI) refers to the quantity of material required per unit of service, expressed here as tonnes per gigawatt. The market share of a technology () represents its share within an installed capacity category. For example, offshore wind capacity consists of two technologies, geared and direct-drive turbines, each with its own market share and material intensity.

The amount of recycled materials (RM) is calculated by multiplying each technology’s material outflow by its corresponding recycling rate (RR). This quantity is then subtracted from both the material inflow and the material outflow, as recycled materials remain within the system.

Finally, material demand is expressed as a share of global supply using each material's mean inflow.

## How to use the model

The model consists of two components: the EnergySystems\_Input Excel file, which contains all user-modifiable inputs, and the EnergySystems\_StockFlow Python script, which performs the calculations and allows certain functions to be enabled or disabled.

The first step in using the model is to ensure that the right packages are installed. The package versions are specified in the README file.

The first step in using the model is to ensure that the input file is correctly linked to the Python script. The r' ' approach uses a relative path, which allows the input file to be located easily when placed in the same folder as the Python script. However, as code editors handle paths differently, adjustments may be required.

Next, the run name can be specified through the ModelRun variable, which is used to label the output Excel file containing all material flows. For example, if ModelRun = "Testrun1", the output file will be named stock\_flow\_export\_Testrun1.xlsx. If ModelRun is not changed between runs, the existing file will be overwritten.

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AI-generated content may be incorrect.Please note that the model can take up to a minute to run.

### Scenario

**Historical stock and scenarios**

The historical stock and the selected scenario determine how much of each technology is installed in a given year. Historical stock values, based on (CBS, 2020, 2024), indicate which technologies have already been installed.

For future developments of the Dutch energy system, the model includes four standard scenarios from (Warnaars, 2025):

* KM – Middle of the Road, aligned with the Dutch National Energy Plan (Economische Zaken en Klimaat, 2023)
* GB – Mutual Balance
* HA – Horizon Supply
* EV – Self-Reliance

In addition, three empty templates (Scenarios X, Y, and Z) are provided for creating custom scenarios.

Once a scenario is selected, it is merged with the historical stock to produce annual installed capacities from 2000 to 2050.

1. Interpolation of values
   * Missing years are filled using interpolation.
   * Available methods include linear (default), quadratic, cubic, and polynomial (see pandas documentation for further information: <https://pandas.pydata.org/docs/reference/api/pandas.DataFrame.interpolate.html>).
   * While polynomial interpolation is commonly applied in dMFA studies, linear interpolation is set as default because it more clearly visualises changes in the scenario.
2. Template format requirements
   * The scenario templates must be followed exactly.
   * Any deviations will result in errors during later calculations.
   * Missing values must be left as empty cells rather than entered as zeros, otherwise interpolation will be incorrect.
3. Recycling options
   * Users must specify whether recycling is included in the model by setting Recycling\_enabled to True or False
   * Recycling disabled: total material inflows and outflows are shown.
   * Recycling enabled: inflows and outflows are lower, as part of the outflow is immediately returned to the system as inflow.

### Handling Model parameters

All model parameters: material intensity, lifetime, market share, recycling rates, and global supply, are implemented dynamically. This means that each parameter can vary from year to year. Because the base model includes 12 types of installed capacities, 38 materials, and 50 years, a large volume of data is required to populate all values.

To manage this, a colour code is used for parameter values:

* **Green**: values for that year are based directly on literature.
* **Black**: present-day values are taken from literature, but not for that specific year.
* **Red**: arbitrary placeholders are used, meaning further data collection or assumptions are needed.
* **Grey**: Template cells which can be used to add values for new (sub) technologies and materials.

### Material Intensity, Market Share and Lifetime

Each technology has its own sheet in the input Excel file, all following a similar structure and including references, notes, and assumptions.

For example, in the case of solar PV, the top of the template provides material intensities for state-of-the-art technologies. Solar PV is divided into four main sub-technologies: C-Si, A-Si, CdTe, and CIGS, each with different material intensities.

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AI-generated content may be incorrect.Material intensities for most technology types is provided in tonnes per gigawatt (t/GWh). For storage technologies, which are batteries (Home, Grid, Vehicle-to-Grid and Redox Flow) and Compressed Air Energy Storage, Material intensities are provided in tonnes per gigawatthour (t/GWh).

A screenshot of a spreadsheet

AI-generated content may be incorrect.Below the material intensities, the market share and lifetime of each technology are listed for every year. The market share indicates the fraction of the installed capacity accounted for by each sub-technology.

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AI-generated content may be incorrect.The material intensity of each sub-technology is multiplied by its corresponding market share and then linked to the *dMaterial Intensity* sheet. The *dMaterial Intensity* sheet contains the actual data used to calculate material flows.

When working with static material intensities (MI), values can be directly modified in the individual technology sheet (e.g. *Solar PV*). For larger adjustments, such as incorporating dynamic MI, the values in the *dMaterial Intensity* sheet can be overridden to insert any desired data.It is important to note that the **data input must follow a fixed structure as deviations will cause errors** in the calculations.

The uncertainty of a technology’s lifetime is represented by the standard deviation (STD) of a normal distribution. In many dynamic material flow analyses, the STD is explicitly incorporated. However, reliable data for this parameter is often difficult to obtain. For this reason, the STD for all technologies is arbitrarily set to 1, but it can be adjusted in the *Standard Deviation* sheet.

A higher STD widens the survival curve, meaning that technologies are retired over a broader time span. Conversely, a lower STD narrows the curve, concentrating end-of-life around the mean lifetime.

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## Addition of Technologies and Parameters

To add new (sub)technologies and materials, the following steps need to be taken.

### Addition of technology types

Technology types are the groups of technologies for which installed capacities are specified, such as Onshore Wind, Solar PV or nuclear energy. To add a new one, for example hydro energy, the following steps need to be taken. For all alterations, check whether the changes are updated in the blue sheets. If not, automatic updating of formulas might need to be enabled in the Excel settings.

1. Go to the *Parameter Labels* sheet and fill in the desired name under  *technology 1*. *A screenshot of a computer

   AI-generated content may be incorrect.*
2. Then go the orange sheet *Tech 1,* and fill in the template by entering the material intensities, market shares and lifetime. If the technology type has only one sub technology, fill in a market share of 1 under the *Alternative 1* cell.

### Addition of Sub technologies

Subtechnologies, such as a new solar PV cell or a different wind turbine can be added with the following steps:

1. Open the desired technology type, such as Solar PV in the corresponding orange sheet
2. A screenshot of a chart

   AI-generated content may be incorrect.Enter the name of the new sub technology in the *Alternative*  *1* fields at material intensity and market share and fill the grey values

### Addition of Materials

If a desired material is not included in the model, take the following steps:

1. Go the *Parameter Labels* sheet. All the way to the right of materials, you can find Material 1, Material 2, etc. Fill in the desired name.

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1. Go the Orange sheets to fill in the Material Intensities of that material for technology. Leave 0 if unknown. The name of the material should be updated to the name entered in *Parameter Labels.*

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1. A table with numbers and letters

   AI-generated content may be incorrect.Go the purple *Global Supply* sheet and fill in the global supply values for the material

## Data Interpretation and Extraction

All relevant data that can be extracted from the Python model is structured in a consistent manner. For further use of the model outcomes, one can directly work in the Python or use the built in extraction of the relevant data into a structured excel document.

The python model works as followed. First, the installed capacities are calculated, the material flows and finally the percentage of global supply. The data for each step is stored in dataframe for either the Inflow, Outflow or Net Addition to Stock (NAS). As mentioned before, recycling can be enabled or disabled at the top of the python code and all recycled materials directly subtracted from both the inflow and the outflow, but are stored in their respective dataframe. The relevant dataframes are named accordingly and all technologies are added up together to form the System dataframe.

All relevant outputs from the Python model are structured consistently. Users can either continue working in Python or export the results to a structured Excel file using the built-in extraction.

Model workflow

1. Installed capacities
   * The model first computes annual installed capacities for each technology.
2. Material flows
   * Based on the stock-driven approach, the model then calculates inflow, outflow, and net additions to stock (NAS).
3. Share of global supply
   * Finally, the model derives the percentage of global supply associated with the calculated material demands.

Data storage

* Each step’s results are stored in dataframes for Inflow, Outflow, and NAS.
* Recycling can be enabled or disabled at the top of the Python code. When enabled, recycled materials are immediately subtracted from both inflow and outflow while also being recorded in their respective recycling dataframe.
* Dataframes are named consistently, and technology-level results are aggregated into a System dataframe that represents the total across all technologies. See example below:

Example data storage: Inflow

* InflowCapacities
* InflowMaterials
  + InflowMaterialsSystem
* InflowPercentage
  + InflowPercentageSystem

### Extraction to Excel

All relevant dataframes are stored in an excel output file which can be named differently for each model run. At the top of the code one can select specific name:

this example results then in an output file called: stock\_flow\_export\_Testrun1.xlsx within the same folder as the code.

The output Excel file includes a pivot table that allows for visualization of individual materials and technologies. It should be noted that only one flow is selected at a time a by default all three are selected.

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## Limitations

The model has several limitations. Not all technologies are included, with key exclusions being hydrogen pipelines, Carbon Capture and Storage (CCS), and the electricity grid. In addition, not all technology parameters are researched to the same extent due to data availability. For example, material intensities (MI) for wind turbines are far better documented than for compressed air energy storage. This is particularly evident for power-to-heat, where only air-source heat pumps are considered, and for redox flow batteries, where vanadium is assumed to dominate the market. In the latter case, MI only account for vanadium in the electrolyte, using experimental energy-density data to determine the amount of electrolyte required.

Several modelling choices and assumptions must also be noted. Market shares are primarily derived from EU sources, yet these may vary across individual countries. The model excludes electricity and fuel imports, even though exporting countries still require materials to produce them. For instance, imported hydrogen does not generate material demand within the model, while in reality the exporting country still requires materials for hydrogen production. This obscures the reliance on these materials, which remains present despite the omission.

Further limitations arise from assumptions in the scenario design and model construction. All dynamic parameters intended to capture future developments are subject to substantial uncertainty, as actual developments will inevitably differ from expectations. It is therefore essential that future users update these parameters as new information becomes available.

## Bibliography

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