COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

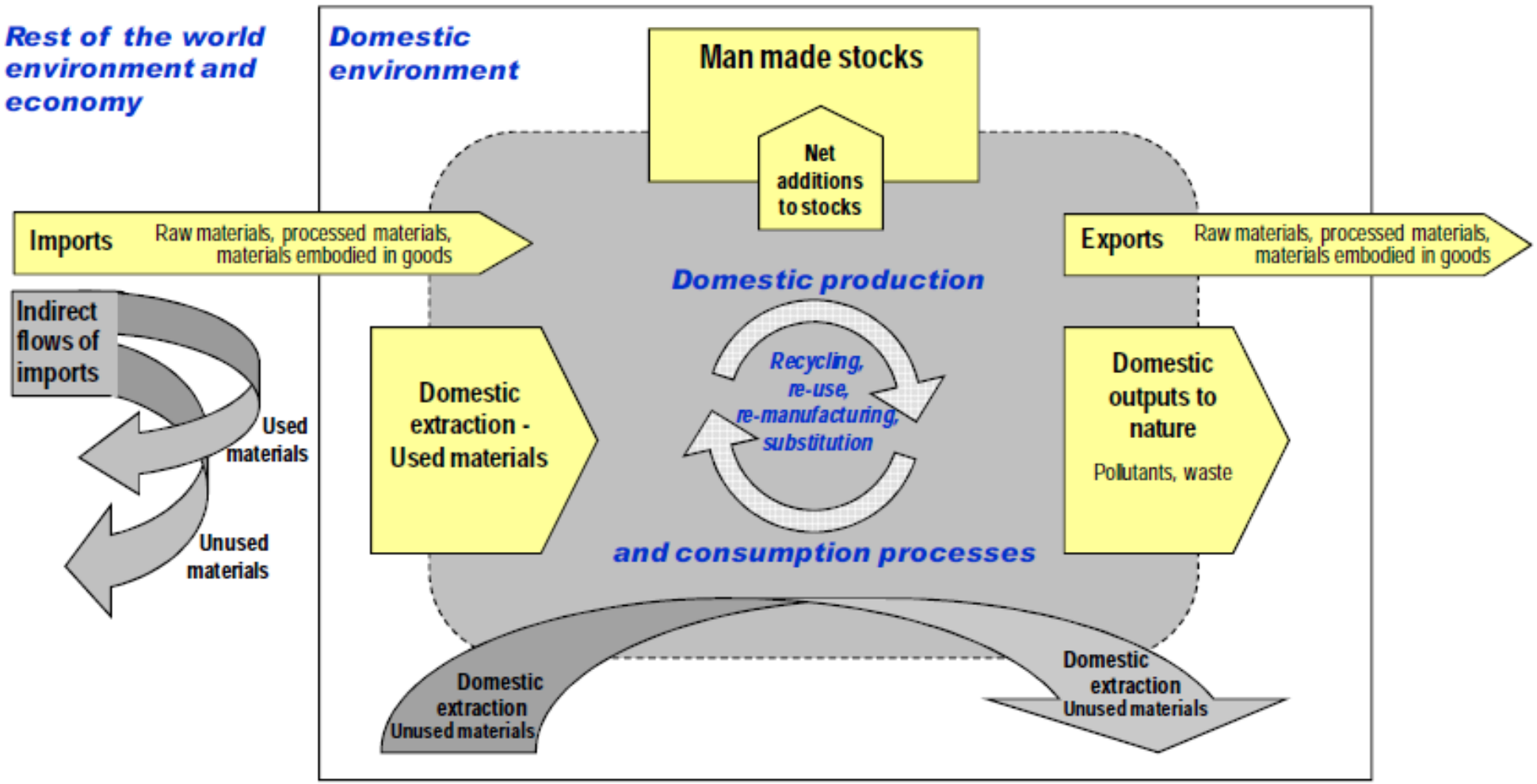
Modeling Demand for Metals

Mineral Model

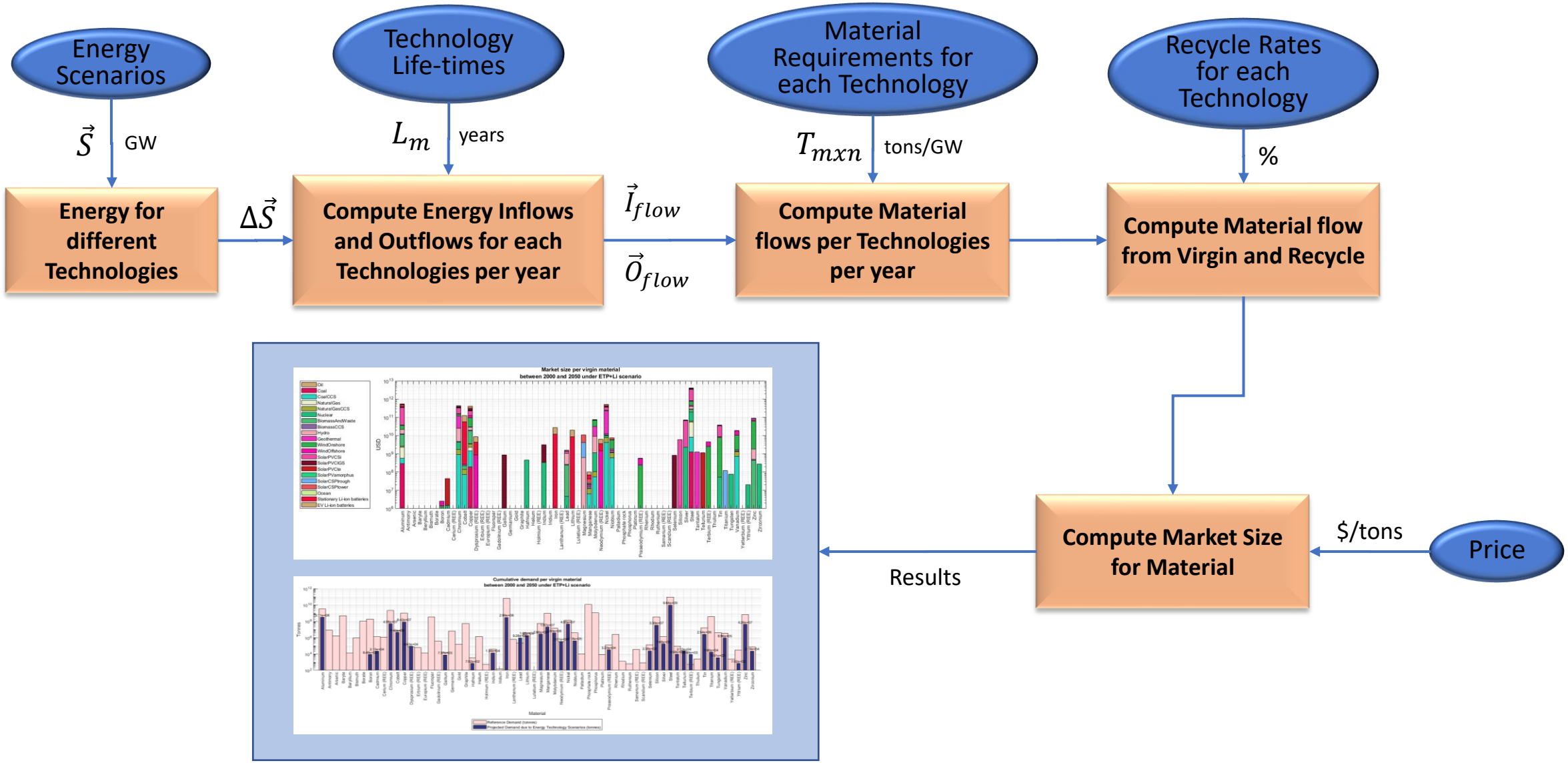
Model Architecture

- There is a growing body of work on modelling the demand for metals and minerals of the energy transition, but the existing efforts leave questions on the impact this demand has on economies and ecosystems, as well as the way changes in technologies and mining approaches will impact outcomes
  - These modelling effort will create a robust and flexible model, grounded in the engineering expertise of the Colorado School of Mines to answer these technical, economic, environmental and social questions
- The principle concept underlying the economy-wide MFA approach is a simple model of the interrelation between the economy and the environment, in which the economy is an embedded subsystem of the environment dependent on a constant throughput of materials and energy
  - Raw materials, water and air are extracted from the natural system as inputs, transformed into products and finally re-transferred to the natural system as outputs (waste and emissions)

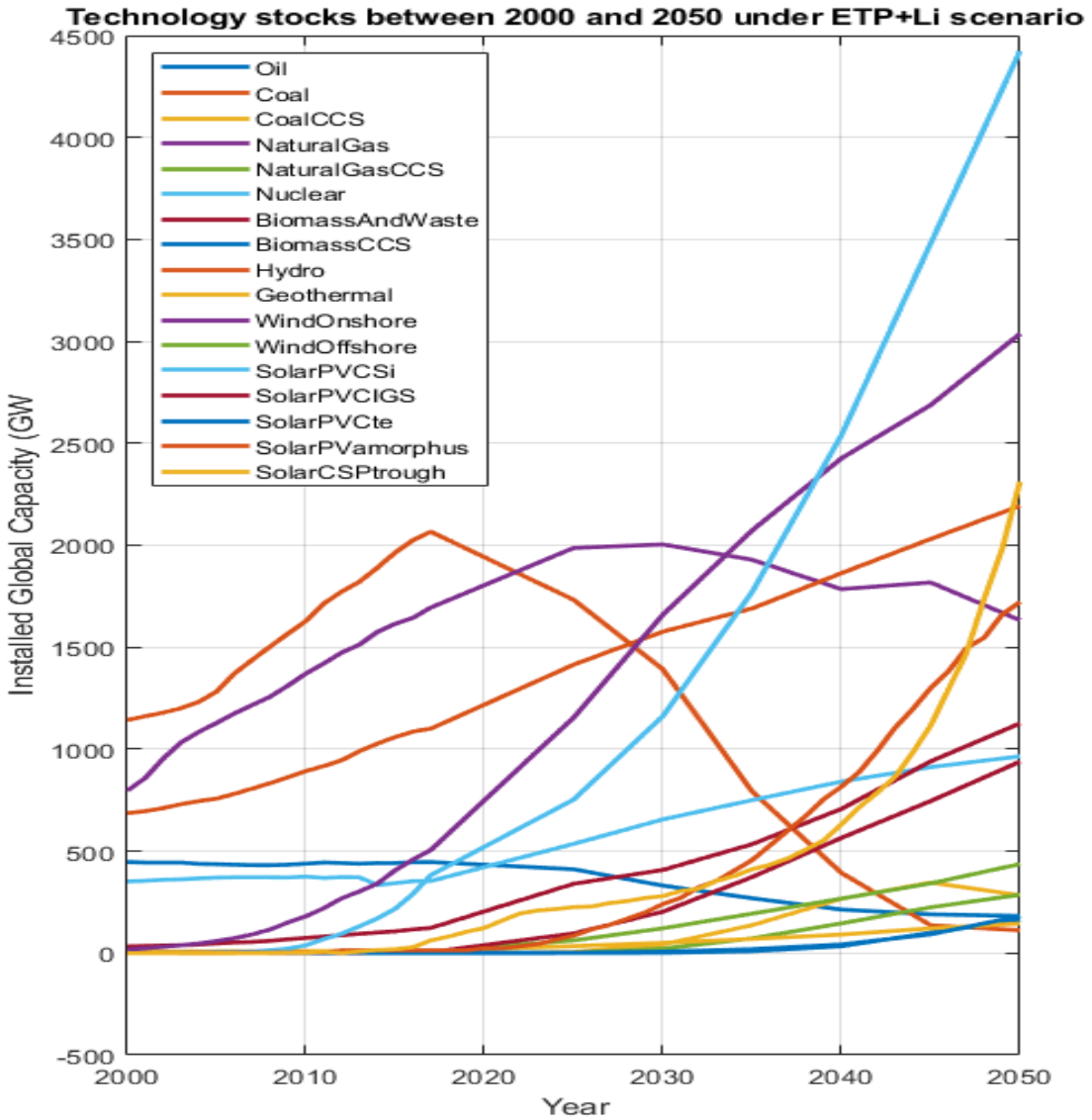
Economy-wide material balance scheme

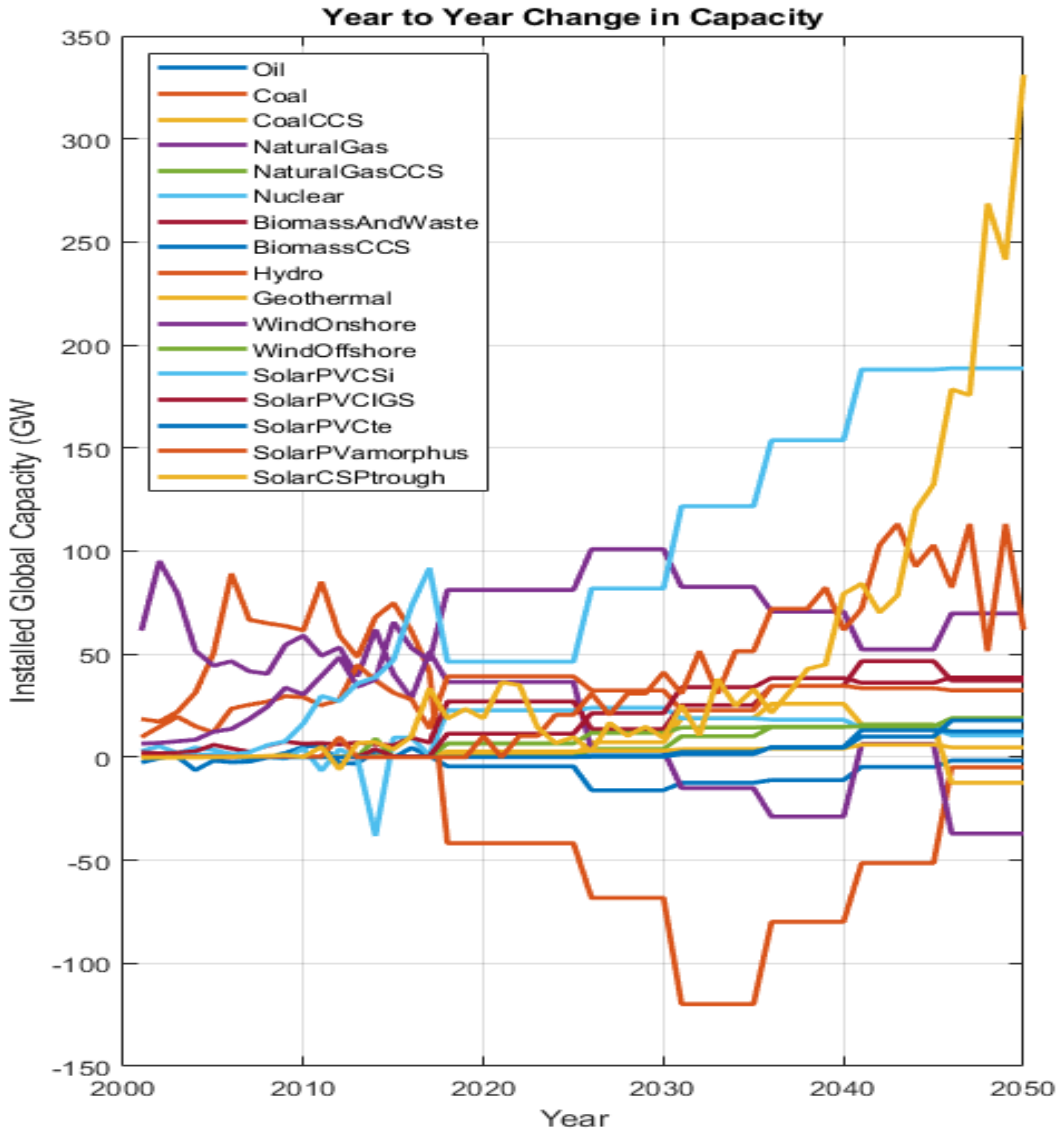


Mineral Model Architecture



Raw Stocks and Year to Year Change





Mineral Model Architecture

Energy Scenarios

$\vec{S}$ GW

Energy for different Technologies

$\Delta\vec{S}$

Technology Life-times

L_m years

Compute Energy Inflows and Outflows for each Technologies per year

$\vec{I}_{flow}$

$\vec{O}_{flow}$

Material Requirements for each Technology

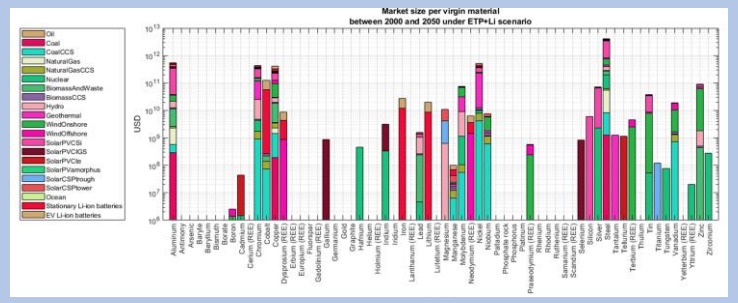
T_{mxn} tons/GW

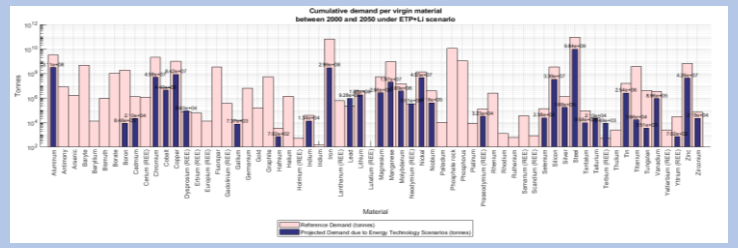
Compute Material flows per Technologies per year

Recycle Rates for each Technology

%

Compute Material flow from Virgin and Recycle





Results

Compute Market Size for Material

$/tons

Price

Basic Model: Compute Energy Inflows & Outflows

$$\Delta\vec{S} = [V]\{\vec{I}_{flow}\} \quad ; \quad \Delta S_i = S_i - S_{i-1} \quad ; \quad i = 1{:}\,p\,, where\ p = years\ from\ start$$

$$\{\vec{I}_{flow}\} = V^{-1}\Delta\vec{S}$$

$$\vec{O}_{flow} = \vec{I}_{flow} - \Delta\vec{S}$$ ➡ Outflow is what is left-over from the inflow

} Per Technology

$$V = \begin{bmatrix} 1 & 0 & 0 & & & & & & \\ -g_1 & 1 & 0 & & & 0 & & & 0 \\ -g_2 & -g_1 & 1 & & & & & & \\ -g_3 & -g_2 & -g_1 & 1 & \dots & 0 & & & \\ & -g_3 & -g_2 & -g_1 & 1 & \dots & & 0 & \\ & & & -g_2 & -g_1 & 1 & & & \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ -g_{n-2} & & & & & & -g_1 & 1 & 0 \\ -g_{n-1} & -g_{n-2} & & & & & -g_2 & -g_1 & 1 \end{bmatrix}_{pxp}$$

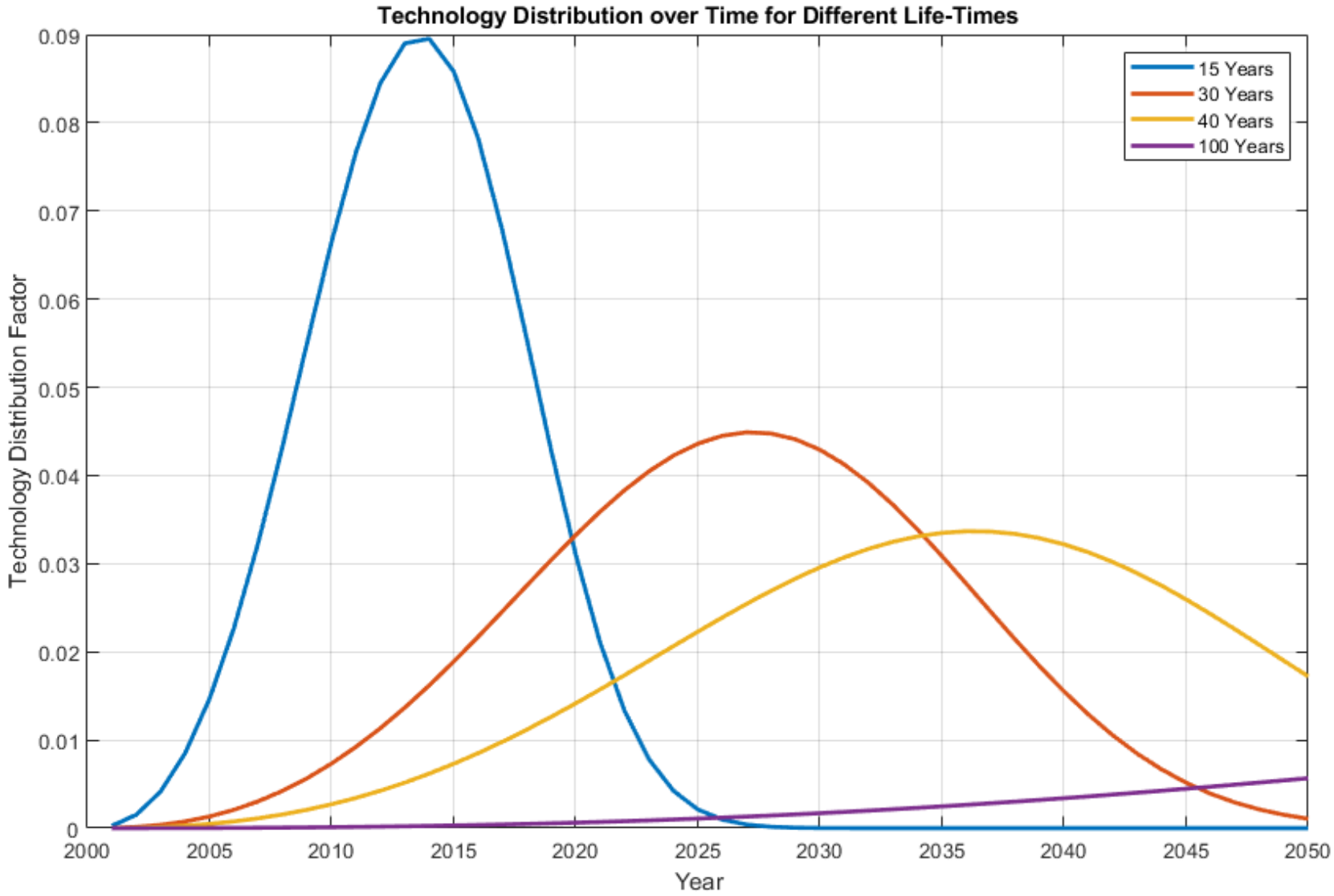
MFA Function: Is the distribution of a technology over its lifetime

$$g_i = \left(\frac{3.5}{L_m}\right)\left(\frac{i}{L_m}\right)^{2.5} \cdot \left(e^{-\left(\frac{i}{L_m}\right)^{3.5}}\right)$$

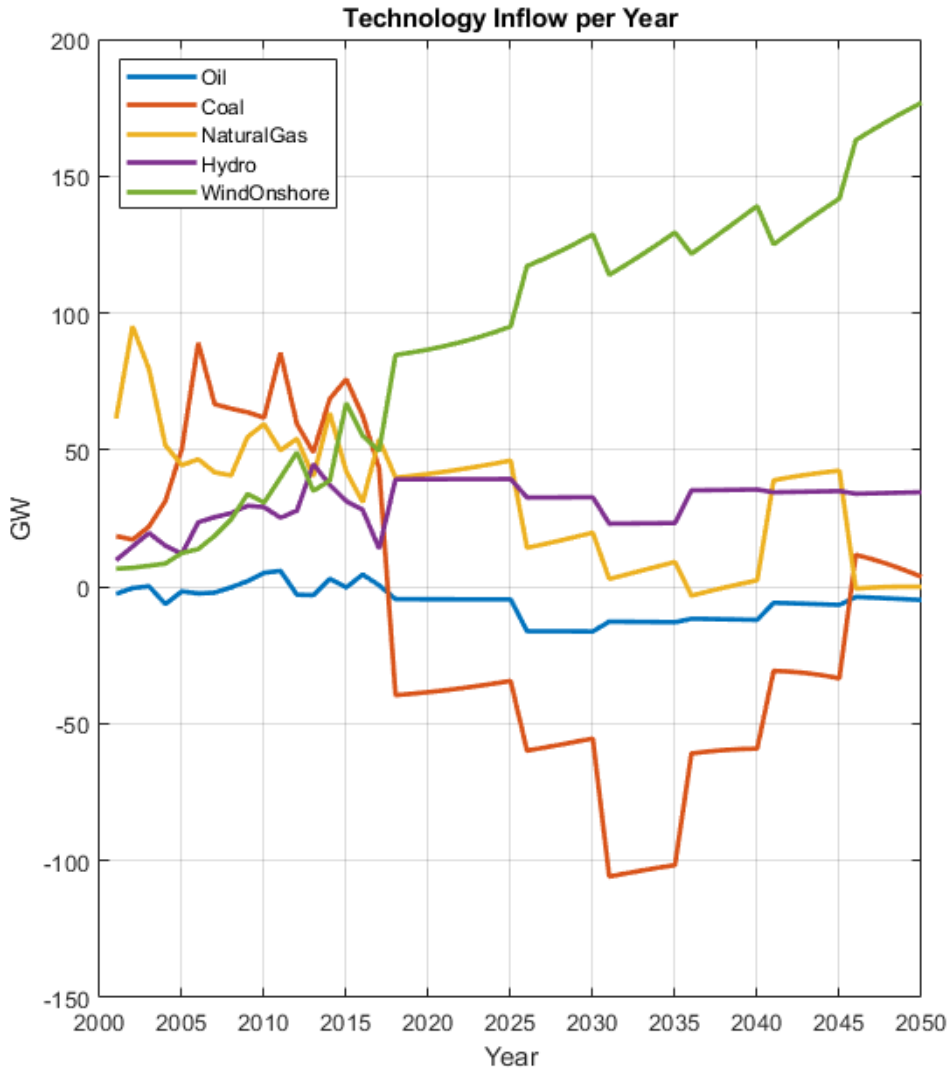
$i = year\ from\ 2000$

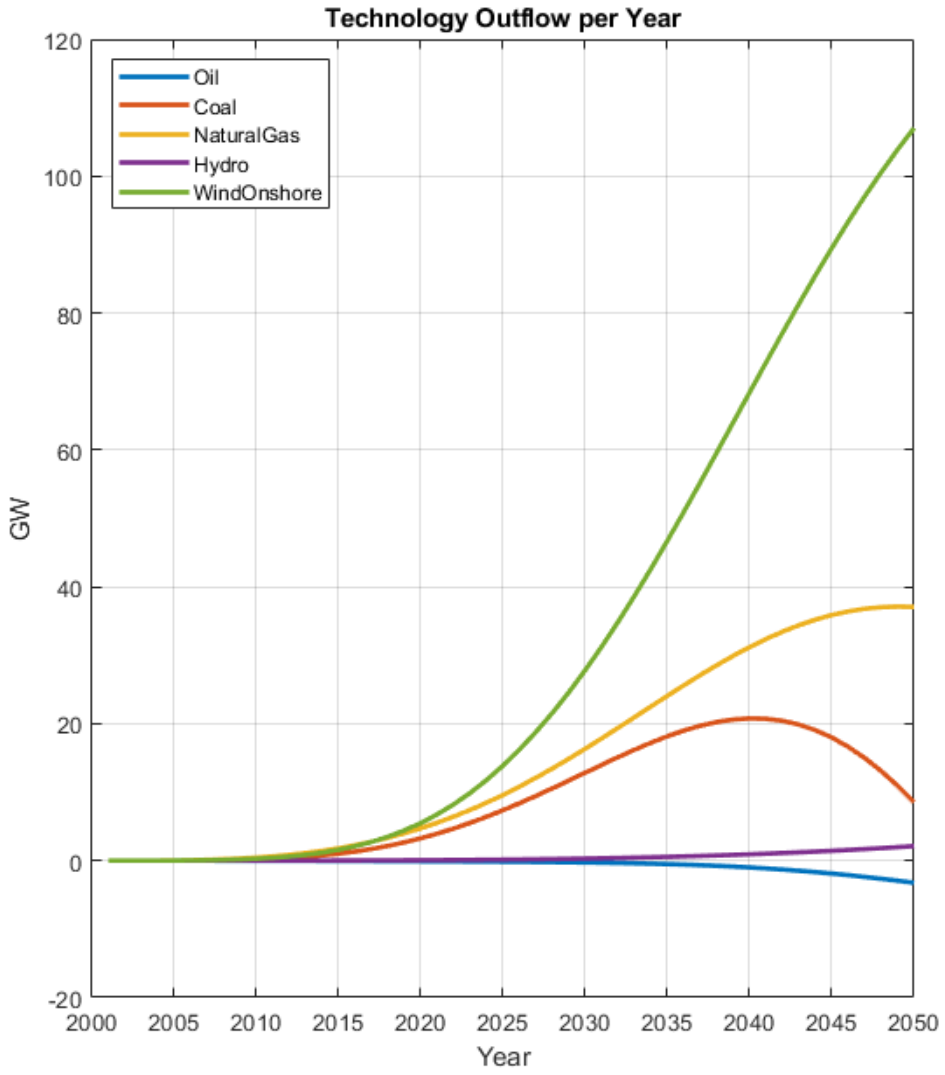
L_m = life-time of the m^{th} technology

MFA as a function of technology life-time



Sample Technology In and Out Flow per Year





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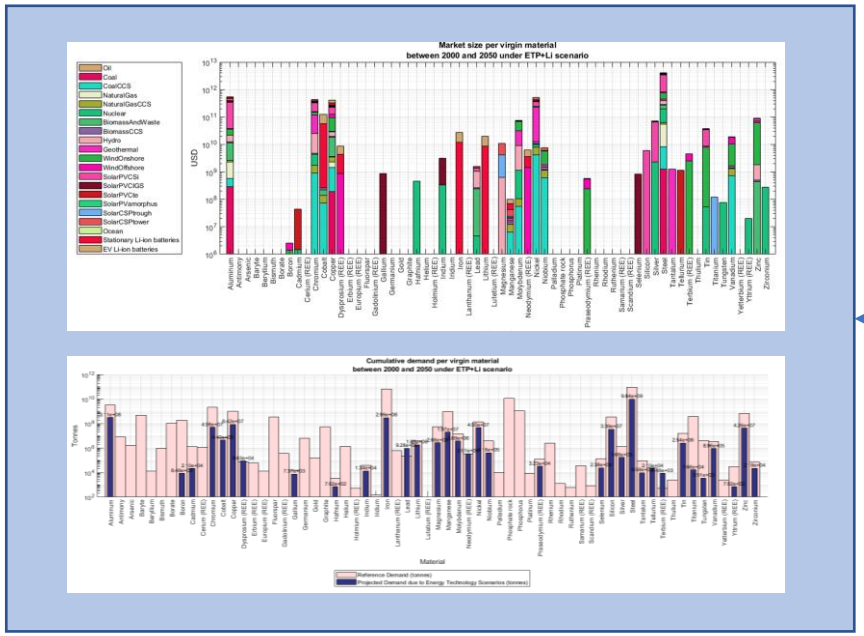


Basic Model: Compute Material Flow

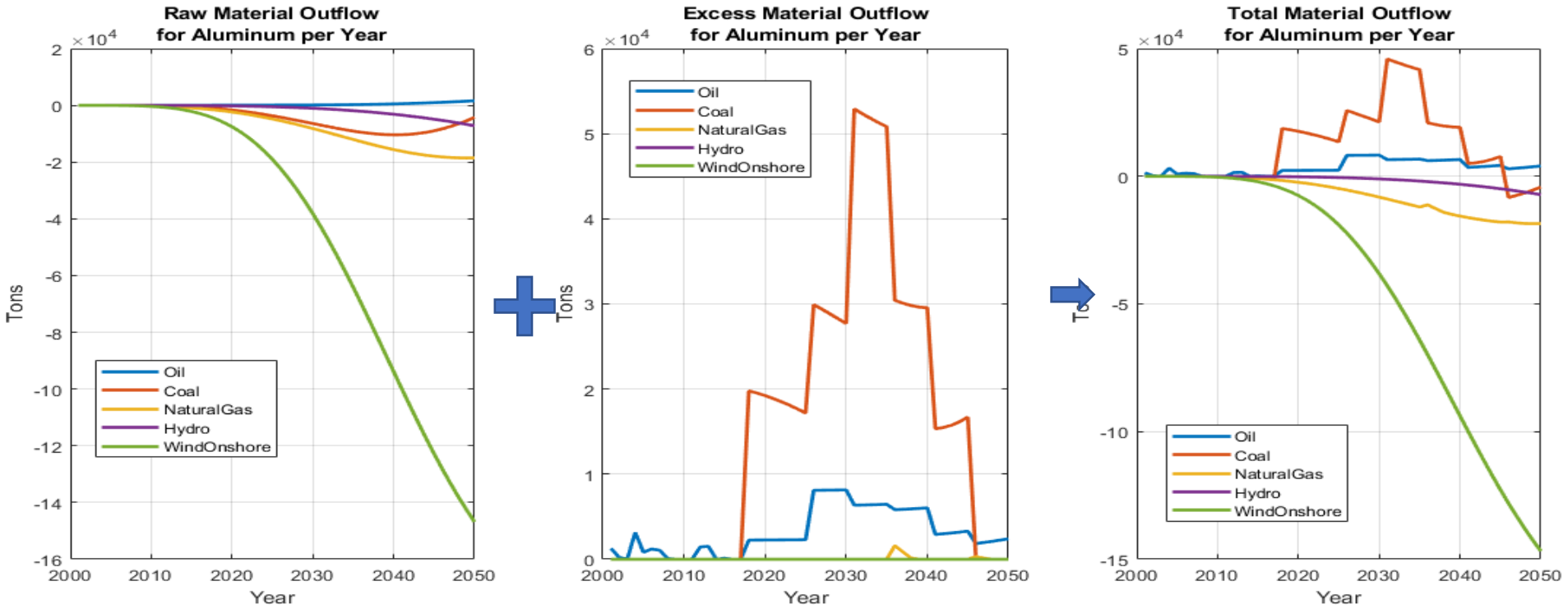
Mineral Flow

$$B_{Inflow_{ijk}} = \vec{I}_{flow_{ij}} * T_{ik}$$

$$B_{Outflow_{ijk}} = -\vec{O}_{flow_{ij}} * T_{ik}$$

i = ith technology
j = jth year
k = kth mineral

Where T_{ik} is $\frac{tons}{GW}$ per Tech



- Excess Material flow is when the inflow goes negative due to the MFA function
- Finally sum across all technologies to get total material flow for each mineral per each year

Material Market Size