Supplementary Material

Appendix I: Derivation of Equations

Equations of Section 2:

$$PF(t) = \frac{URR\ b/2}{1 + \cosh\left(b\ (t - t_M)\right)} \tag{S1}$$

$$PF_{net}(t) = PF(t)\frac{R_f(t) - 1}{R_f(t)} \tag{S2}$$

$$PR(t) = \frac{\int_{t_0}^{t} I(t)dt - \frac{1}{L}\int_{t_0}^{t} I(t)dt}{L} R_r(t), \text{ where } R_r(t) = R_r(0)\left(\frac{\int_{t_0}^{t} I(t)dt}{\int_{t_0}^{t_0+1} I(t)dt}\right)^{\gamma}$$

$$PR(t) = \frac{\int_{t_0}^{t} I(t)dt - \frac{1}{L}\int_{t_0}^{t} I(t)dt}{L} R_r(0)\left(\frac{\int_{t_0}^{t} I(t)dt}{\int_{t_0}^{t_0+1} I(t)dt}\right)^{\gamma}$$

$$PR(t) = \left(\int_{t_0}^{t} I(t)dt\right)\frac{1 - \frac{1}{L}}{L} R_r(0)\left(\frac{\int_{t_0}^{t} I(t)dt}{\int_{t_0}^{t_0+1} I(t)dt}\right)^{\gamma} \tag{S3}$$

$$PR(t) = \left(\int_{t_0}^{t} I(t)dt\right)^{\gamma+1}\frac{1 - \frac{1}{L}}{L} R_r(0) \cdot c$$

where: $c = \left(\frac{1}{\int_{t_0}^{t_0+1} I(t)dt}\right)^{\gamma} = \left(\frac{1}{I_1}\right)^{\gamma}$constant; $R_r(0) \cdot c \to R_r(\tilde{n})$

In the above two equations, $\left(\int_{t_0}^{t} I(t)dt\right)^{\gamma+1}$ will have the units *(TWh/year)*$^{\gamma+1}$ while c will have the units of *(TWh/year)*$^{-\gamma}$. Since $R_r(0)$ is unitless, $R_r(\tilde{n})$ will also have units of *(TWh/year)*$^{-\gamma}$. This leads to *PR(t)* having units of *(TWh/year)*$^{\gamma+1}$ ·*(TWh/year)*$^{-\gamma}$ = *TWh/year*, as expected. This applies to all mentions of *PR(t)* from this point forward. Since *PR(t)* is the only model variable dependent on $R_r(\tilde{n})$, the unit consistency of the model is preserved.

$$PR(t) = \left(\int_{t_0}^{t} I(t)dt\right)^{1+\gamma}\frac{(L-1)}{L^2} R_r(\tilde{n}) \tag{S4}$$

$$PS_{net}(t) = PF_{net}(t) + PR(t) - I(t) \tag{S5}$$

$$\varepsilon(t) = \frac{I(t)}{PF_{net}(t) + PR(t)} \tag{S6}$$

$$k(t) = \frac{\varepsilon(t) \cdot PR(t) + \frac{1}{Rf(t) - 1} \cdot PF_{net}}{PS_{gross}} \tag{S7}$$

Subtituting Equations (S2), (S4) and (S6) into (S5), we get:

- substracting $I(t)$ from Equation (S6) and rearranging we get: $PF_{net}(t) + PR(t) - I(t) = \frac{I(t)}{\varepsilon(t)} - I(t)$

$$PS_{net}(t) = I(t) \cdot \left[\frac{1}{\varepsilon(t)} - 1\right] = I(t) \cdot \frac{1-\varepsilon(t)}{\varepsilon(t)}$$

$$\varepsilon(t) \cdot PS_{net}(t) = I(t) \cdot [1-\varepsilon(t)]$$

$$\frac{\varepsilon(t)}{1-\varepsilon(t)} \cdot PS_{net}(t) = I(t) \text{ Relation A}$$

- inserting Relation A into Equation (S5) we get the relation:

$$PS_{net}(t) = PF_{net}(t) + PR(t) - \frac{\varepsilon(t)}{1-\varepsilon(t)} \cdot PS_{net}(t)$$

$$PS_{net}(t) = PF_{net}(t) + \left(\int_{t_0}^{t} I(t)dt\right)^{1+\gamma} \frac{(L-1)}{L^2} R_r(\tilde{n}) - \frac{\varepsilon(t)}{1-\varepsilon(t)} \cdot PS_{net}(t)$$

$$\left(1 + \frac{\varepsilon(t)}{1-\varepsilon(t)}\right) PS_{net}(t) = PF_{net}(t) + \left(\int_{t_0}^{t} I(t)dt\right)^{1+\gamma} \frac{(L-1)}{L^2} R_r(\tilde{n})$$

$$\left(\frac{1}{1-\varepsilon(t)}\right) PS_{net}(t) = PF_{net}(t) + \left(\int_{t_0}^{t} I(t)dt\right)^{1+\gamma} \frac{(L-1)}{L^2} R_r(\tilde{n})$$

$$PS_{net}(t) = \left[PF_{net}(t) + \left(\int_{t_0}^{t} I(t)dt\right)^{1+\gamma} \frac{(L-1)}{L^2} R_r(\tilde{n})\right] [1-\varepsilon(t)]$$

$$PS_{net}(t) = \left[PF_{net}(t) + \left(\int_{t_0}^{t} \frac{\varepsilon(t)}{1-\varepsilon(t)} \cdot PS_{net}(t)dt\right)^{1+\gamma} \frac{(L-1)}{L^2} R_r(\tilde{n})\right] [1-\varepsilon(t)]$$

- from the time of the renewables diffusion start, we can consider ε constant. thus:

$$\begin{aligned} PS_{net}(t) &= \left[PF_{net}(t) + \left(\frac{\varepsilon}{1-\varepsilon} \cdot \int_{t_0}^{t} PS_{net}(t)dt\right)^{1+\gamma} \frac{(L-1)}{L^2} R_r(\tilde{n})\right] (1-\varepsilon) PS_{net}(t) \\ &= \left[\frac{URR\,\frac{b}{2}}{1+\cosh\big(b\,(t-t_M)\big)} \cdot \frac{R_f(t)-1}{R_f(t)} \right. \\ &\quad \left. + \left(\frac{\varepsilon}{1-\varepsilon} \int_{t_0}^{t} P_{Snet}(t)dt\right)^{1+\gamma} \frac{(L-1)}{L^2} R_r(\tilde{n})\right] (1-\varepsilon) \end{aligned} \tag{S8}$$

$$PD(t) = \int_0^t \frac{Ib(t)D(t)dt}{n(t)} - \frac{1}{Lb} \int_0^t \frac{Ib(t)\widetilde{D}(t)}{n(t)} dt \tag{S9}$$

$$PS_{net}(t) = PD(t)u(k,t) \tag{S10}$$

where,

PF: fossil energy extraction rate [power: TW or TWh/year];
tM: fossil peak production year;
PFnet: net primary power [power: TW or TWh/year];
EROEI: energy return on energy invested [ratio: dimensionless];

Rf: EROEI of fossil [ratio: dimensionless];
Rr: EROEI of renewable [ratio: dimensionless];
L: renewable energy infrastructure lifetime [years];
PR: renewable energy generation rate [power: TW or TWh/year];
PRmax: maximum renewable energy generation rate (potential) [power: TW or TWh/year];
γ: renewable energy learning rate [dimensionless];
PSnet: net social surplus energy generation rate [power: TW or TWh/year];
ε: renewable energy investment ratio [dimensionless];
I: energy invested in renewable energy generation [energy: TWh];
Ib: initial energy invested in renewable energy generation [energy: TWh];
k: the energy cost ratio [dimensionless];
D: energy capacity of the constructed energy-consuming capital [energy: TWh];
PD: energy consumption rate of the energy-consuming capital [power: TW or TWh/year];
u: energy stock utilization [fraction: diemnsionless].

Equations of Section 3:

$$\sum_i ER_i \cdot c_i < C_{max} \tag{S11}$$

$$PR_j(t) < PR_{j\_max} \tag{S12}$$

$$\begin{aligned} PS_{net}(t) &= \left(\int_0^t \frac{Ib(t)D(t)dt}{n(t)} - \frac{1}{Lb}\int_0^t \frac{Ib(t)\widetilde{D}(t)}{n(t)}dt\right)u(k,t) \\ &\geq PD_{min}N(t) \;\&\; \left|\frac{du(k,t)}{dt}\right| < lim \end{aligned} \tag{S13}$$

$$\begin{aligned} &PS_{net}(t) \\ &= \left[\frac{URR\frac{b}{2}}{1+\cosh\left(b\,(t-t_M)\right)} \cdot \frac{R_f(t)-1}{R_f(t)} \right. \\ &\left. + \left(\frac{\varepsilon}{1-\varepsilon}\int_{t_0}^{t} P_{Snet}(t)dt\right)^{1+\gamma} \frac{(L-1)}{L^2} R_r(\tilde{n})\right](1-\varepsilon) \geq PD_{min}N(t) \end{aligned} \tag{S14}$$

$$FD(t_0)\frac{i(i+1)^y}{(i+1)^y-1}y\frac{E(t_0)}{Y(t_0)} \leq \int_{t_0}^{t_0+L} I(t_0)dt \cdot \frac{L-1}{L^2}R_r(t_0) \tag{S15}$$

inserting Relation A into Equation (S15) we get the relation:

$$\begin{aligned} &FD(t_0)\frac{i(i+1)^n}{(i+1)^n-1}n\frac{\int_{t_0}^{t_0+1} PS_{net}(t)dt}{Y(t_0)} \\ &\quad \leq \int_{t_0}^{t_0+L}\left(\int_{t_0}^{t_0+1}\frac{\varepsilon}{1-\varepsilon}\cdot P_{Snet}(t)dt\right)dt \cdot \frac{L-1}{L^2}R_r(t_0) \end{aligned} \tag{S16}$$

$$\frac{FD(t_0)}{Y(t_0)} \leq \frac{\varepsilon}{1-\varepsilon} \cdot \frac{L^2-1}{L} R_r(t_0) \cdot \frac{(i+1)^n-1}{i(i+1)^n\, n}$$

$$\frac{FD(t_0)}{Y(t_0)} \leq \frac{\varepsilon}{1-\varepsilon} \cdot \left(L - \frac{1}{L}\right) R_r(t_0) \cdot \frac{(i+1)^n - 1}{i(i+1)^n\, n} \tag{S17}$$

$$\frac{P_{Snet}(t)}{N(t)} \geq 2000W \;\&\; \left|\frac{\Delta k(t)}{\Delta t}\right| < 5\% \;\&\; k(t) < 3\% \tag{S18}$$

Where

URR: ultimately recovarable reserves [energy: TWh];
SRR: safely recovarable reserves [energy: TWh];
ER: reserves burned without pollution control [energy: TWh];
CS: reserves saved through capture [energy: TWh];
PDmin: minimun per capita energy consumption rate threshold [power: TW or TWh/year];
N: population size [people];
FD: public and private debt issuance rate [monetary: $/year];
Y: current consumption rate [monetary: $/year];
Y/E: energy intensity [$/TWh].

Appendix II: SET Model Documentation

Figure A1 presents the SET model structure. The variables' naming convention is referenced from the main paper. Auxiliary variables not present in the paper equations are named in a way that is descriptive.

The SET model is structured into 5 modules:

- the fossil power module calculates oil, gas and coal power generation, based on the *cosh* model suggested by Maggio & Cacciola (2009) and Cavallo (2004) and as defined in Equation (S1).
- the renewable power module—is the core of the SET model; calculates renewable power generation, installation and decommission rates, based on investment ratio *epsilon* and total power *P*. It is important to mention that before the start (*ren_start*) of the enacting of renewable energy policy, *epsilon* takes values from a table function *epsilontable*, corresponding to the fitted values of installed, existing renewable energy power up until that date. After that, *epsilon* will transition to the value of *epsilon_static* (as defined in experiment setup page).
- the emissions module sums and cumulates emissions from all energy sources
- the unit conversion module ensures unit consistency throughout the model
- the helper module ensures model continuity—as the energy investment into renewable power has a policy delay time *policy_label* (as defined in the experiment setup page), the smooth transition of the system from the former state into the latter is achieved, using a Bass-diffusion model, spanning over the time period *policy_label*. The transition of epsilon from taking values from the *epsilontable* to *epsilon_static* follows a similar diffusion model. In a similar fashion, when the CO2 cap is turned *on*, the helper module ensures that the reduction rate of fossil fuel sources is smooth and continuous (through the *co2_policy_adjuster* variable).

Figure A1. SET model structure.

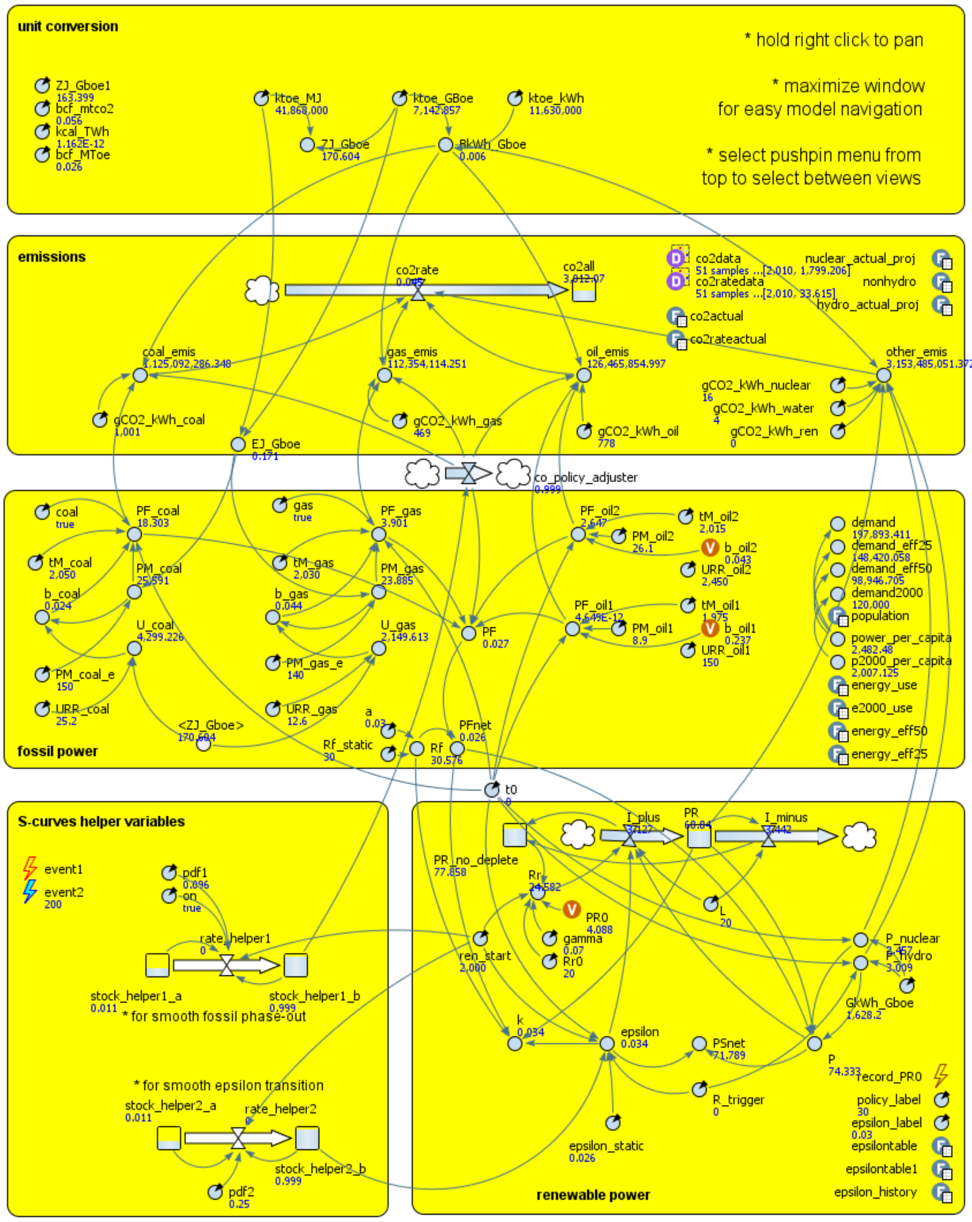
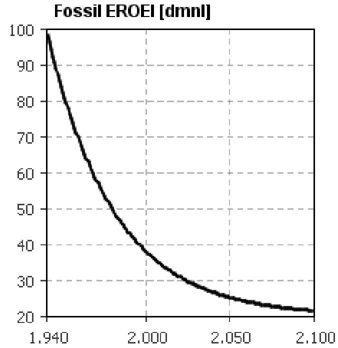
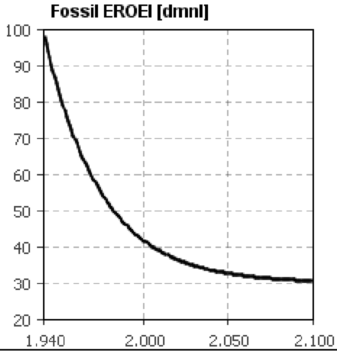


Table A1 presents the equations for the key variables of the model, including the correspondence to the paper (if applicable).

Table A1. SET model equations.

Number	Variable	Corresponding equation	Expression
1	PF	Equation (S1)	PF_oil1 + (PF_oil2 + PF_coal + PF_gas) × (1 − co_policy_adjuster)
2	PF_oil1	-	2 × PM_oil1/(1 + cosh(b_oil1 × (time() − (tM_oil1-t0))))
3	PF_oil2	-	2 × PM_oil2/(1 + cosh(b_oil2 × (time() − (tM_oil2-t0))))
4	PF_gas	-	2 × PM_gas/(1 + cosh(b_gas × (time() − (tM_gas-t0))))
5	PF_coal	-	2 × PM_coal/(1 + cosh(b_coal × (time() − (tM_coal-t0))))
6	PFnet	Equation (S2)	PF × (Rf − 1)/Rf

Table A1. *Cont.*

<table>
<tr><th>Number</th><th>Variable</th><th>Corresponding equation</th><th colspan="2">Expression</th></tr>
<tr><td>7</td><td>PR</td><td>Equation (S3)</td><td colspan="2">INTEG[(I_plus − I_minus)dt]</td></tr>
<tr><td>8</td><td>I_minus</td><td>Equation (S3)</td><td colspan="2">PR/L</td></tr>
<tr><td>9</td><td>I_plus</td><td>Equation (S6)</td><td colspan="2">Epsilon × P × (Rr/L)</td></tr>
<tr><td>10</td><td>k</td><td>Equation (S7)</td><td colspan="2">(epsilon × PR+1/(Rf-1) × PFnet)/(PFnet + PR)</td></tr>
<tr><td>11</td><td>Rr</td><td>Equation (S3)</td><td colspan="2">Rr0 × pow((PR/PR0), gamma))</td></tr>
<tr><td>12</td><td>PSnet</td><td>Equation (S6)</td><td colspan="2">P × (1 − epsilon)</td></tr>
<tr><td>13</td><td>P</td><td>Equation (S8)</td><td colspan="2">PR + PFnet + P_hydro + P_nuclear</td></tr>
<tr><td rowspan="3"><u>14</u></td><td rowspan="3">Rf</td><td rowspan="3">-</td><td colspan="2">(100−Rf_static) × exp(−a × (time() − 1940)) + Rf_static [a]</td></tr>
<tr><td>Uncapped

</td><td>Carbon Capped

</td></tr>
<tr><td>a = 0.025, Rf_static = 20</td><td>a = 0.03, Rf_static = 30</td></tr>
</table>

[a] Exponential time decay estimate for compound EROEI of all fossil energy sources, constructed based on fossil EROEI estimates of Murphy and Hall [1], Gagnon, Hall and Brinker [2] and Gupta and Hall [3].

Table A2. SET model parameter assumptions.

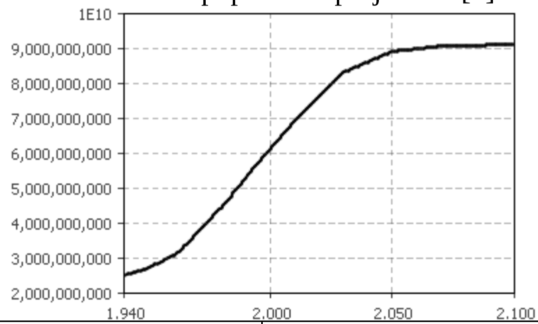
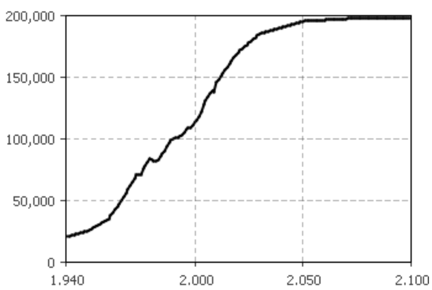
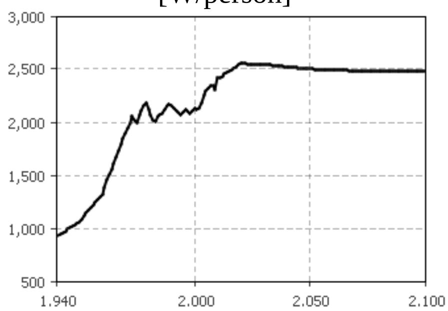
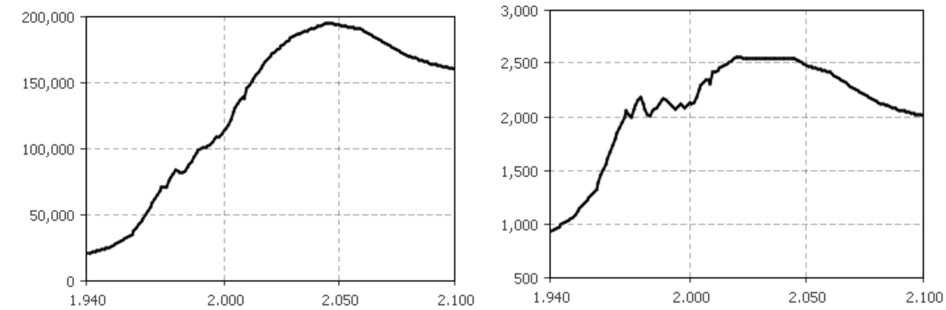
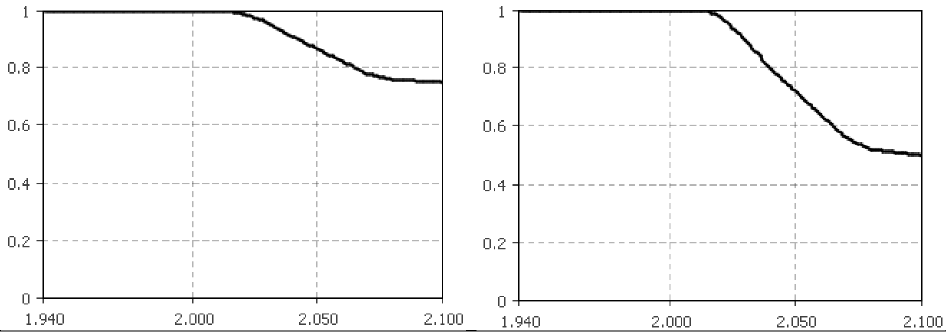
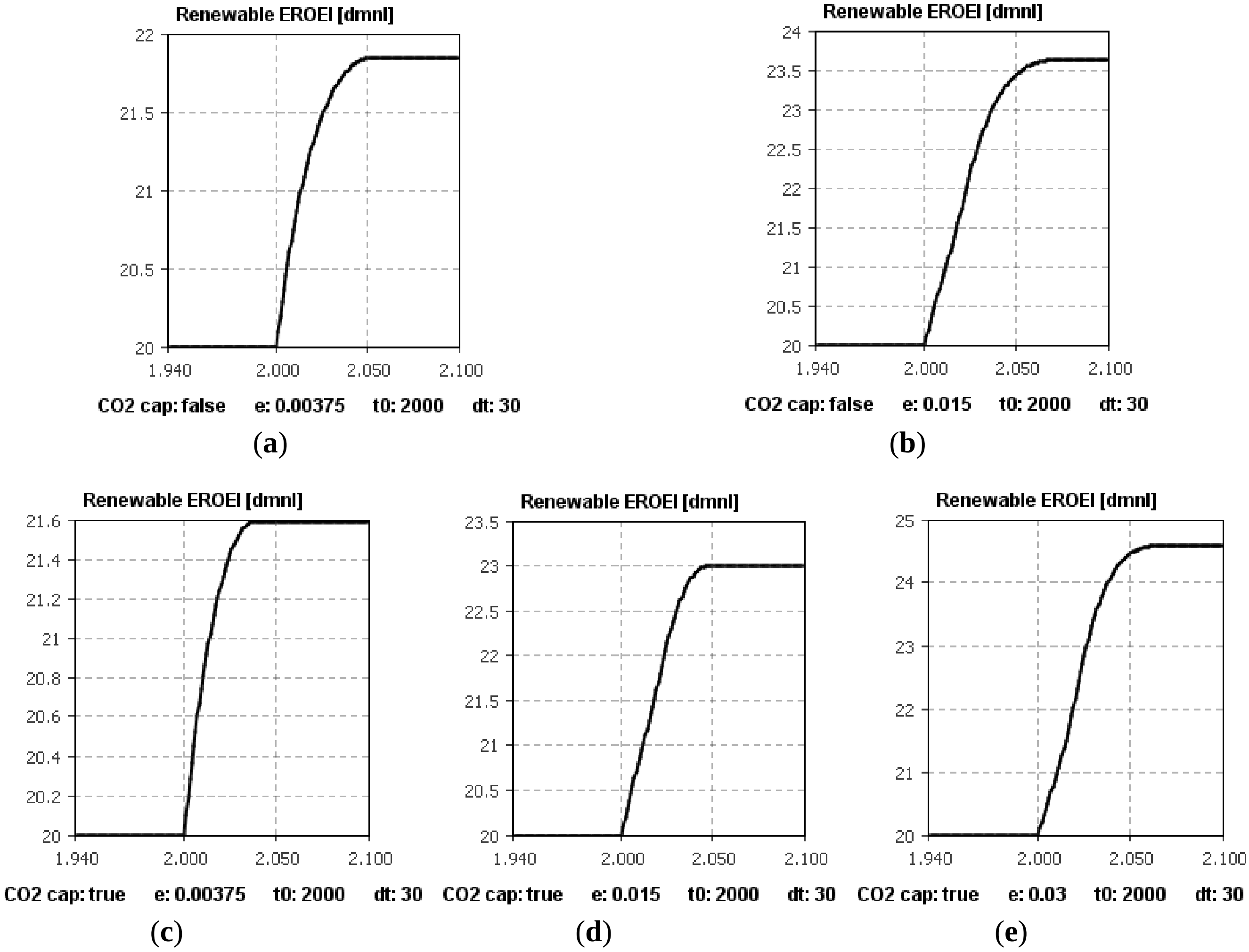
<table>
<tr><td>1</td><td>population</td><td colspan="2">UN medium population projection [4]
</td></tr>
<tr><td>2</td><td>energy_use</td><td>World energy demand [TWh] historical [5] 2011 projection [6]
</td><td>corresponding per capita power [W/person]
</td></tr>
</table>

Table A2. *Cont.*

3	e2000_use	World energy demand under "2000W society" [TWh] 
4	energy_eff25 energy_eff50	Transition assumption for 25%/50% energy efficiency improvement 
5	CO_2 rateactual CO_2 actual	CO_2 rateactual: Actual CO_2 emission rate [Gt CO_2/year] [7] CO_2 actual: integral of CO_2 rateactual, I(0) = 784 [Gt CO_2]
6	tM_coal	2050 peak year [8]
7	tM_gas	2030 peak year [8]
8	tM_oil1	1975 peak year [9]
9	tM_oil2	2009 peak year [8]
10	URR_coal	4300 [Gboe] ultimately recoverable reserves [8]
11	URR_gas	2150 [Gboe] ultimately recoverable reserves [8]
12	URR_oil1	150 [Gboe] ultimately recoverable reserves [9]
13	URR_oil2	2100 [Gboe] ultimately recoverable reserves [9]
14	PM_coal	25.6 [Gboe/year] peak production (power) [8]
15	PM_gas	23.8 [Gboe/year] peak production (power) [8]
16	PM_oil1	8.9 [Gboe/year] peak production (power) [9]
17	PM_oil2	26.1 [Gboe/year] peak production (power) [9]

For reference we provide the dynamics of the RE EROEI *Rr*, based on $\gamma = 0.07$, for each scenario (Figure A3).

Figure A3. Renewable EROEI (R_r) Dynamics For Different Scenarios. (**a–b**) Uncapped; (**c–e**) Carbon capped.



The SET model is available online for trials at this link: http://www.runthemodel.com/models/1418/ (requires JAVA, with security settings set to "medium" or lower to run—required by AnyLogic) and *.alp AnyLogic model files are available from the authors upon request.

Reference

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