EROI at different analysis boundaries and Net energy (services) long-term trend of UK

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Two topics on net energy measures

- Gross and Net Energy Ratios (GER, NER) of economy as system boundary expands
  - Mimic Costanza and Herendeen (1980, 1984) to calculate energy intensities
  - Use energy intensities to calculate GER and NER of economy

- Energy Intensity Ratio (EIR) of long-term time series of UK energy and energy services
  - 1500 to 2000
  - EIR is proxy for net energy ratio (= EROI – 1)
  - Roger Fouquet (2008) *Heat, Power, and Light*

GER and NER of energy as boundary of analysis expands

Net energy ratios can be calculated based on energy intensities, ε

$$\vec{\varepsilon}X + \vec{E}_{earth} = \vec{\varepsilon}\hat{X}$$

such that

$$\vec{\varepsilon} = \vec{E}_{earth}\left(\hat{X} - X\right)^{-1}$$

- **X = transactions matrix**
  - **can have units of energy for energy sectors**
- **Xhat = diagonal of gross production each sector**
- ***ε* = vector of energy intensities**
  - **"Gross energy extracted/Net energy output"**
- **E_{earth} = gross energy extraction**

Net energy ratios can be calculated based on energy intensities, ε

- With ε = "Gross energy extracted/Net energy output"

Gross Energy Ratio (GER)

$$EROI = GER = \frac{E_{out}}{E_{in}} = \frac{\varepsilon}{\varepsilon - 1}$$

Net Energy Ratio (NER)

$$NER = \frac{E_{out} - E_{in}}{E_{in}} = \frac{1}{\varepsilon - 1} = GER - 1$$

Assume process information with oil, NG, and "other" sectors

$$E_{\text{earth}} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

$$X = \begin{array}{cl} \begin{bmatrix} 0 & 0 & 1.0 & 0 & 0 \\ 0 & 0 & 0 & 1.0 & 0 \\ 0.02 & 0.07 & 0 & 0 & 0.02 \\ 0.05 & 0 & 0.06 & 0 & 0.08 \\ 0.014 & 0.013 & 0.006 & 0.005 & 0 \end{bmatrix} & \begin{array}{l} \text{Oil extraction} \\ \text{NG extraction} \\ \text{Oil refining} \\ \text{NG processing} \\ \text{“Other”} \end{array} \end{array}$$

Assume process information with oil, NG, and "other" sectors

$$\hat{X} = \begin{bmatrix} E_{\text{Gross oil}} & 0 & 0 & 0 & 0 \\ 0 & E_{\text{Gross NG}} & 0 & 0 & 0 \\ 0 & 0 & E_{\text{Gross refined oil}} & 0 & 0 \\ 0 & 0 & 0 & E_{\text{Gross distributed NG}} & 0 \\ 0 & 0 & 0 & 0 & E_{\text{Gross other}} \end{bmatrix}$$

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$$\hat{X} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0.95 & 0 & 0 \\ 0 & 0 & 0 & 0.97 & 0 \\ 0 & 0 & 0 & 0 & 0.038 \end{bmatrix}$$

Each energy intensity represents a slightly different interpretation for net energy

$$\vec{\varepsilon} = E_{\text{earth}}(\hat{X} - X)^{-1}$$

$$\vec{\varepsilon} = \begin{bmatrix} \frac{E_{\text{Gross oil}}}{E_{\text{Net oil}}} & \frac{E_{\text{Gross oil}}}{E_{\text{Net NG}}} & \frac{E_{\text{Gross oil}}}{E_{\text{Net refined oil}}} & \frac{E_{\text{Gross oil}}}{E_{\text{Net distributed NG}}} & \frac{E_{\text{Gross oil}}}{E_{\text{Net `other'}}} \\ \frac{E_{\text{Gross NG}}}{E_{\text{Net oil}}} & \frac{E_{\text{Gross NG}}}{E_{\text{Net NG}}} & \frac{E_{\text{Gross NG}}}{E_{\text{Net refined oil}}} & \frac{E_{\text{Gross NG}}}{E_{\text{Net distributed NG}}} & \frac{E_{\text{Gross NG}}}{E_{\text{Net `other'}}} \end{bmatrix}$$

$$\vec{\varepsilon} = \begin{bmatrix} 1.038 & 0.087 & 1.103 & 0.094 & 0.779 \\ 0.091 & 1.044 & 0.180 & 1.088 & 2.386 \end{bmatrix}$$

IN REVIEW

Each energy intensity represents a slightly different interpretation for net energy

$$\vec{\varepsilon} = E_{\text{earth}}(\hat{X} - X)^{-1}$$

$$\vec{\varepsilon} = \begin{bmatrix} \frac{E_{\text{Gross oil}}}{E_{\text{Net oil}}} & \frac{E_{\text{Gross oil}}}{E_{\text{Net NG}}} & \frac{E_{\text{Gross oil}}}{E_{\text{Net refined oil}}} & \frac{E_{\text{Gross oil}}}{E_{\text{Net distributed NG}}} & \frac{E_{\text{Gross oil}}}{E_{\text{Net 'other'}}} \\ \frac{E_{\text{Gross NG}}}{E_{\text{Net oil}}} & \frac{E_{\text{Gross NG}}}{E_{\text{Net NG}}} & \frac{E_{\text{Gross NG}}}{E_{\text{Net refined oil}}} & \frac{E_{\text{Gross NG}}}{E_{\text{Net distributed NG}}} & \frac{E_{\text{Gross NG}}}{E_{\text{Net 'other'}}} \end{bmatrix}$$

IN REVIEW

$$GER_{\frac{\text{Primary energy}}{\text{Net oil}}} = \frac{\varepsilon_{\frac{\text{Gross total primary}}{\text{Net oil}}}}{\varepsilon_{\frac{\text{Gross total primary}}{\text{Net oil}}} - 1} = \frac{\frac{E_{\text{Gross oil}}}{E_{\text{Net oil}}} + \frac{E_{\text{Gross NG}}}{E_{\text{Net oil}}}}{\frac{E_{\text{Gross oil}}}{E_{\text{Net oil}}} + \frac{E_{\text{Gross NG}}}{E_{\text{Net oil}}} - 1} = 8.75$$

$$NER_{\frac{\text{Primary energy}}{\text{Net oil}}} = \frac{1}{\varepsilon_{\frac{\text{Gross total primary}}{\text{Net oil}}} - 1} = \frac{1}{\frac{E_{\text{Gross oil}}}{E_{\text{Net oil}}} + \frac{E_{\text{Gross NG}}}{E_{\text{Net oil}}} - 1} = 7.75$$

Energy return ratios (ERRs) are most meaningful when considering total gross primary energy production

ERRs considering *TOTAL* gross primary energy extraction

ERR	Equation	Value
$\text{GER}_{\frac{\text{Primary energy}}{\text{Net oil}}}$	$\frac{\varepsilon_{1,1}+\varepsilon_{2,1}}{\varepsilon_{1,1}+\varepsilon_{2,1}-1}$	8.75
$\text{NER}_{\frac{\text{Primary energy}}{\text{Net oil}}}$	$\frac{1}{\varepsilon_{1,1}+\varepsilon_{2,1}-1}$	7.75
$\text{GER}_{\frac{\text{Primary energy}}{\text{Net refined oil}}}$	$\frac{\varepsilon_{1,3}+\varepsilon_{2,3}}{\varepsilon_{1,3}+\varepsilon_{2,3}-1}$	4.53
$\text{NER}_{\frac{\text{Primary energy}}{\text{Net refined oil}}}$	$\frac{1}{\varepsilon_{1,3}+\varepsilon_{2,3}-1}$	3.53
$\text{GER}_{\frac{\text{Primary energy}}{\text{Net NG}}}$	$\frac{\varepsilon_{2,2}+\varepsilon_{1,2}}{\varepsilon_{2,2}+\varepsilon_{1,2}-1}$	8.64
$\text{NER}_{\frac{\text{Primary energy}}{\text{Net NG}}}$	$\frac{1}{\varepsilon_{2,2}+\varepsilon_{1,2}-1}$	7.64
$\text{GER}_{\frac{\text{Primary energy}}{\text{Net distributed NG}}}$	$\frac{\varepsilon_{2,4}+\varepsilon_{1,4}}{\varepsilon_{2,4}+\varepsilon_{1,4}-1}$	6.49
$\text{NER}_{\frac{\text{Primary energy}}{\text{Net distributed NG}}}$	$\frac{1}{\varepsilon_{2,4}+\varepsilon_{1,4}-1}$	5.49

ERRs considering *ONE type* gross primary energy extraction

ERR	Equation	Value
$\text{GER}_{\frac{\text{Gross oil}}{\text{Net oil}}}$	$\frac{\varepsilon_{1,1}}{\varepsilon_{1,1}+\varepsilon_{2,1}-1}$	8.04
$\text{NER}_{\frac{\text{Gross oil}}{\text{Net oil}}}$	$\frac{1}{\varepsilon_{1,1}+\varepsilon_{2,1}-1}$	7.75
$\text{GER}_{\frac{\text{Gross oil}}{\text{Net refined oil}}}$	$\frac{\varepsilon_{1,3}}{\varepsilon_{1,3}+\varepsilon_{2,3}-1}$	3.90
$\text{NER}_{\frac{\text{Gross oil}}{\text{Net refined oil}}}$	$\frac{1}{\varepsilon_{1,3}+\varepsilon_{2,3}-1}$	3.53
$\text{GER}_{\frac{\text{Gross NG}}{\text{Net NG}}}$	$\frac{\varepsilon_{2,2}}{\varepsilon_{2,2}+\varepsilon_{1,2}-1}$	7.97
$\text{NER}_{\frac{\text{Gross NG}}{\text{Net NG}}}$	$\frac{1}{\varepsilon_{2,2}+\varepsilon_{1,2}-1}$	7.64
$\text{GER}_{\frac{\text{Gross NG}}{\text{Net distributed NG}}}$	$\frac{\varepsilon_{2,4}}{\varepsilon_{2,4}+\varepsilon_{1,4}-1}$	5.97
$\text{NER}_{\frac{\text{Gross NG}}{\text{Net distributed NG}}}$	$\frac{1}{\varepsilon_{2,4}+\varepsilon_{1,4}-1}$	5.49

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The limiting case of EROI = 1 (GER = 1) is the same as saying GDP = 0

- **Previous GER and NERs assume non-zero demand**

$$\vec{d} = \begin{bmatrix} 0 \\ 0 \\ 0.84 \\ 0.78 \\ 0 \end{bmatrix}$$

- **At zero demand …**
  - **Energy intensities are infinite**
  - **GER = 1 and NER 0 for each energy resource**
  - **Equivalent to saying GDP = 0**

$$\vec{d} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Think about expanding boundary from normal economic I-O formulation

- **Same concept as Costanza and Herendeen (1980, 1984)**

Table 5. Simplified I-O matrix and economic flows for a 2-sector economy.

	Energy Sector 1	'Other' Sectors 2	Final Demand		Total Output
Energy Sector 1	x_{11}	x_{12}	g_1	c_1	x_1
'Other' Sectors 2	x_{21}	x_{22}	g_2	c_2	x_2
Taxes	t_1	t_2	t_G	t_C	T
Wages	l_1	l_2	l_G	l_C	L
Total Outlays	xx_1	xx_2	GG	CC	Y

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Imagine a simple example 2-sector economy

(1 energy sector, 1 'other' sector)

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Table 6. Example values for ERR calculation of expanding boundary

		Energy Sector	'Other' Sectors	Final Demand		Total Output	
		1	2				Units
Energy Sector	1	1	2	1	5	9	energy
'Other' Sectors	2	1	5	1	10	17	any
Taxes		1.2	5.44	0	0	T	any
Wages		l_1	l_2	l_C	l_G	L	any

$$E_{\text{earth}} = \begin{bmatrix} 9 & 0 \end{bmatrix}$$

Table 7. Example values for ERR calculation of expanding boundary

System Boundary	$\varepsilon_{1,1}$	$\varepsilon_{1,2}$	$\varepsilon_{1,3}$	GER	NER
2x2	1.15	0.19	–	7.71	6.71
3x3	1.20	0.30	0.23	6.08	5.08
4x4	∞	∞	∞	1	0

$\varepsilon_{1,1} = E_{\text{gross out}}/E_{\text{net}}$

Finding the ratio of energy price to 'other' price, you can solve for ERRs from ε in units of 'energy/$'

$\varepsilon_{1,1} = E_{gross}/E_{net}$

System Boundary	$\varepsilon_{1,1}$	$\varepsilon_{1,2}$	$\varepsilon_{1,3}$	GER	NER
2x2	1.15	0.19	–	7.71	6.71
3x3	1.20	0.30	0.23	6.08	5.08
4x4	∞	∞	∞	1	0

IN REVIEW

$\varepsilon_{1,1} = E_{gross\ out}/E_{net}$

$\varepsilon_{1,1} = E_{gross\ out}/\$_{net}$

If $p_{energy} = 1$ and

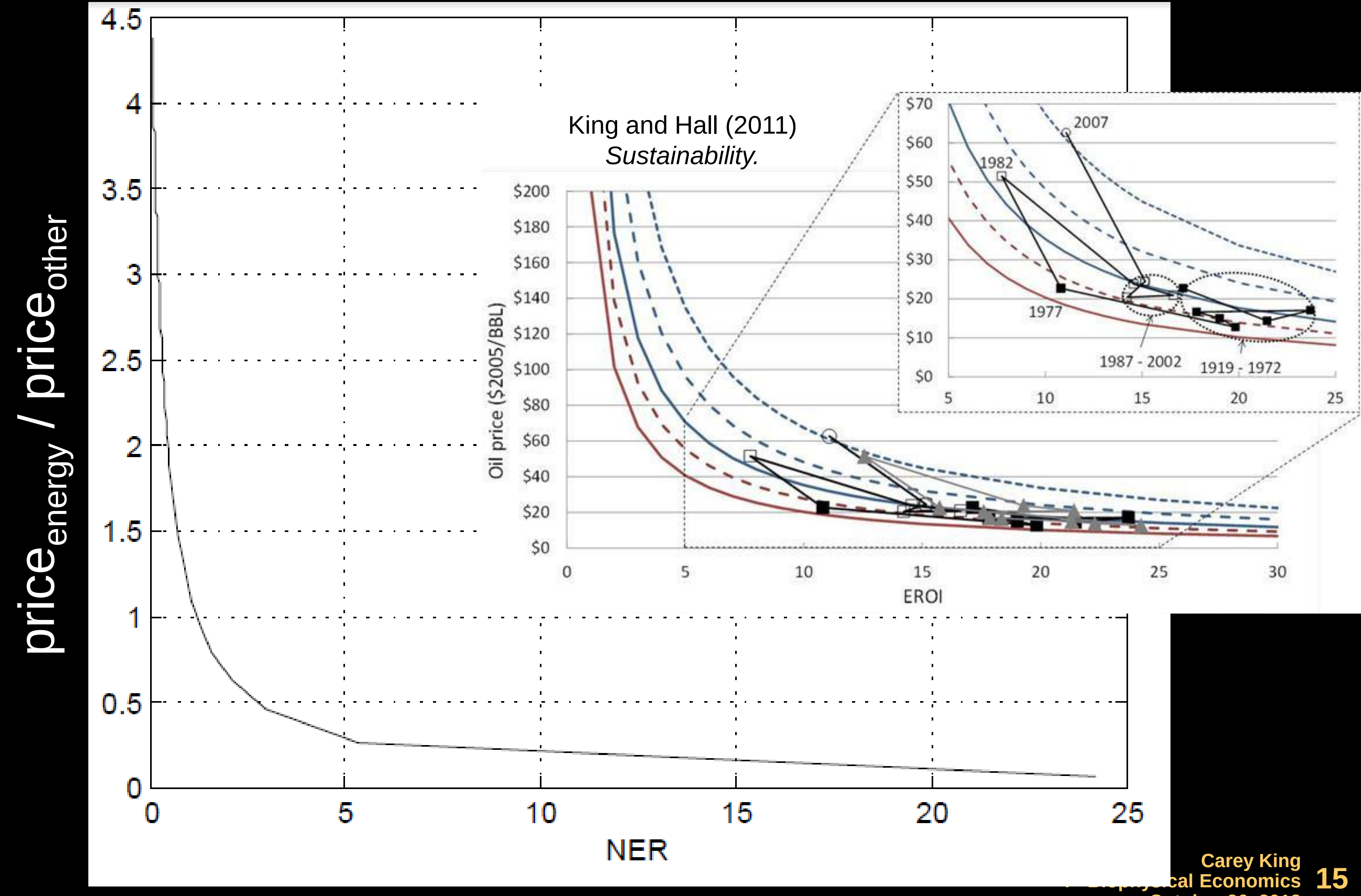
$p_{other} = 4.95$ (2x2)

$p_{other} = 5.54$ (3x3)

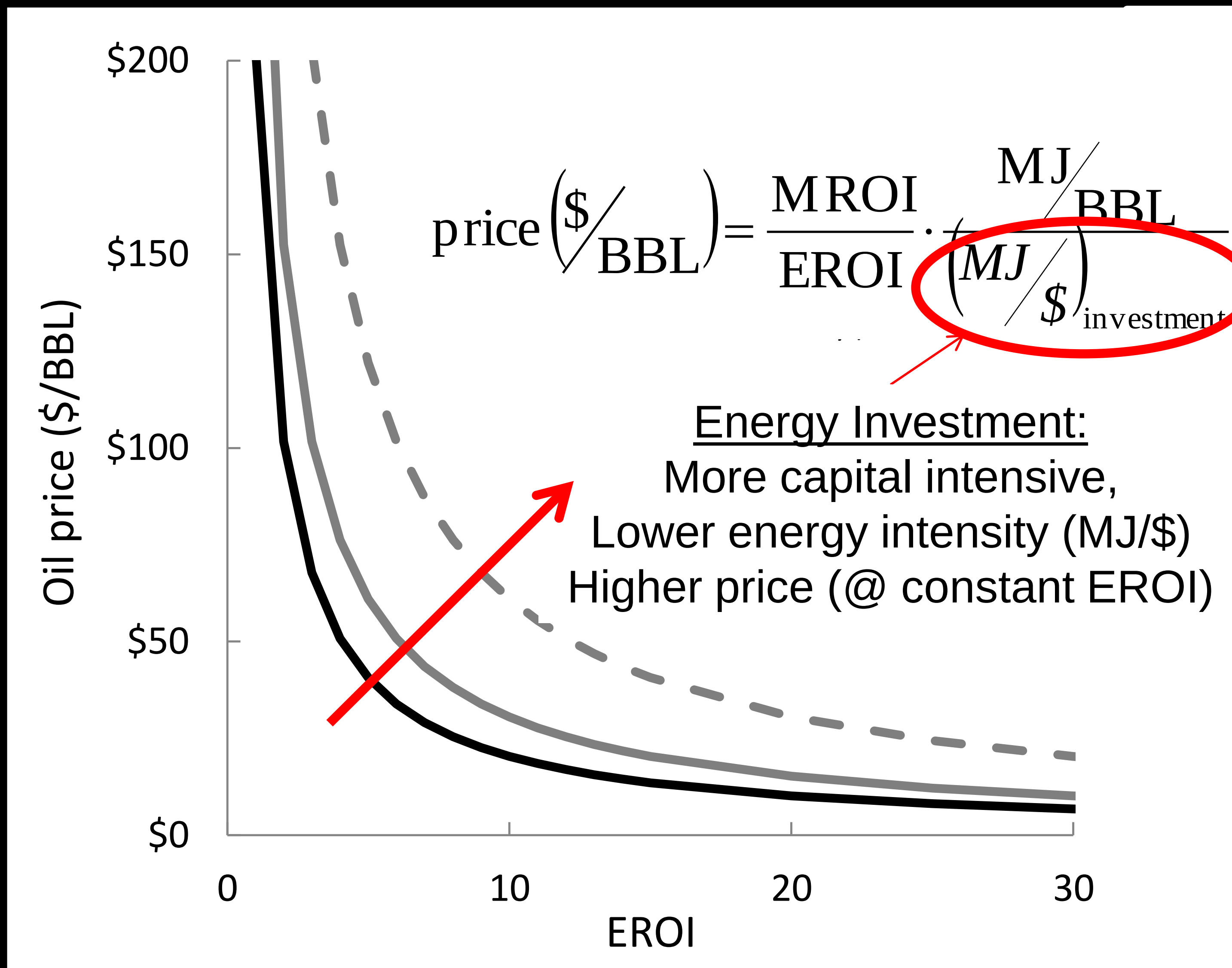
$\varepsilon_{1,1} = E_{gross}/\$_{net}$

System Boundary (or matrix size)	$\varepsilon_{1,1}$	$\varepsilon_{1,2}$	$\varepsilon_{1,3}$	$\varepsilon_{Total\ Economy}$	GER	NER
2x2	1.1489	0.0397	–	0.1472	7.71	6.71
3x3	1.1965	0.0610	0.2255	0.1652	6.08	5.08
4x4	∞	∞	∞	∞	1	0

Assuming a constant demand, we can draw price vs. NER (or GER) curve



Capital intensive energy is more expensive at equal EROI

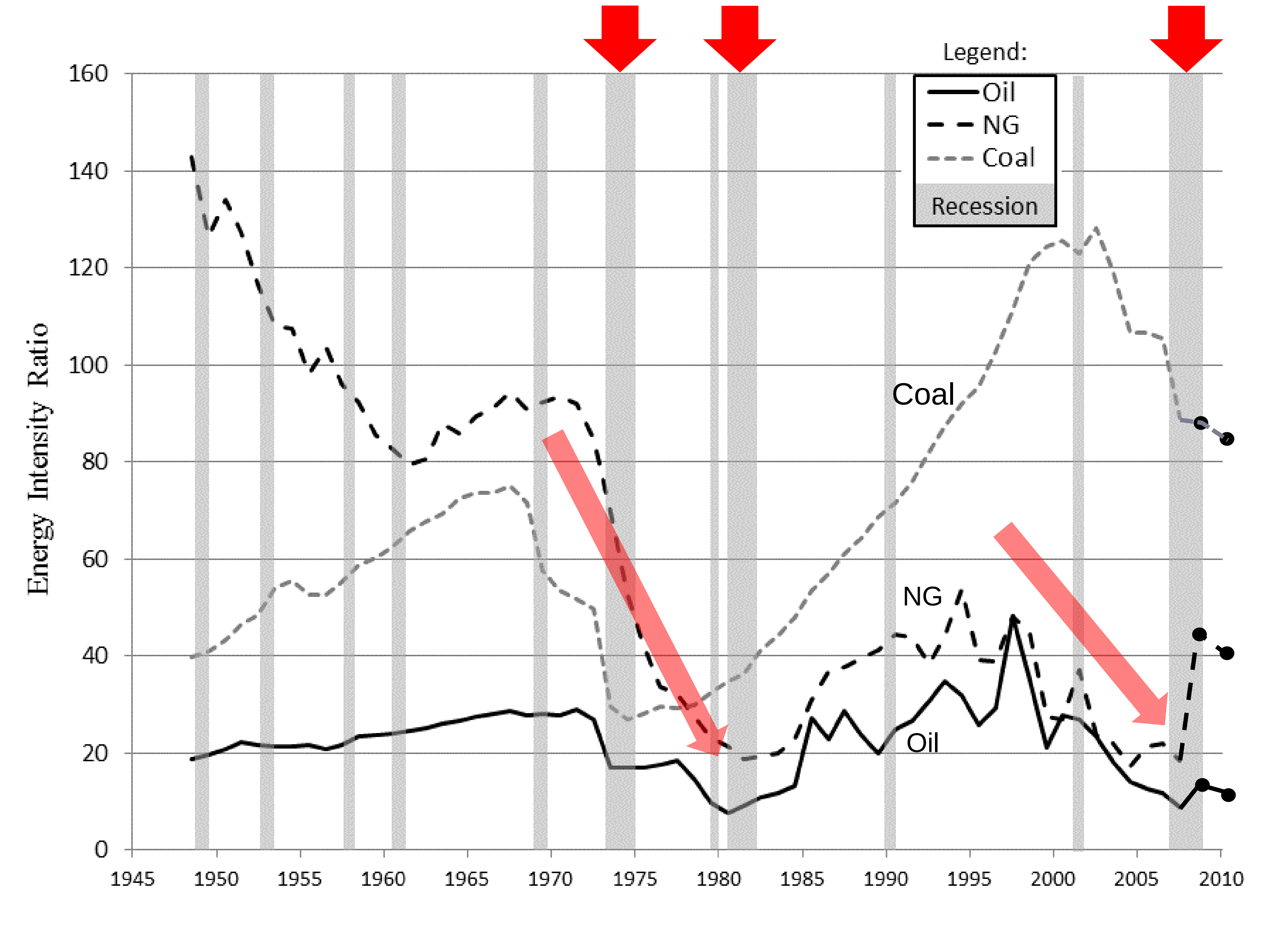


Energy Intensity Ratio (proxy EROI) of UK time series: 1500-2000

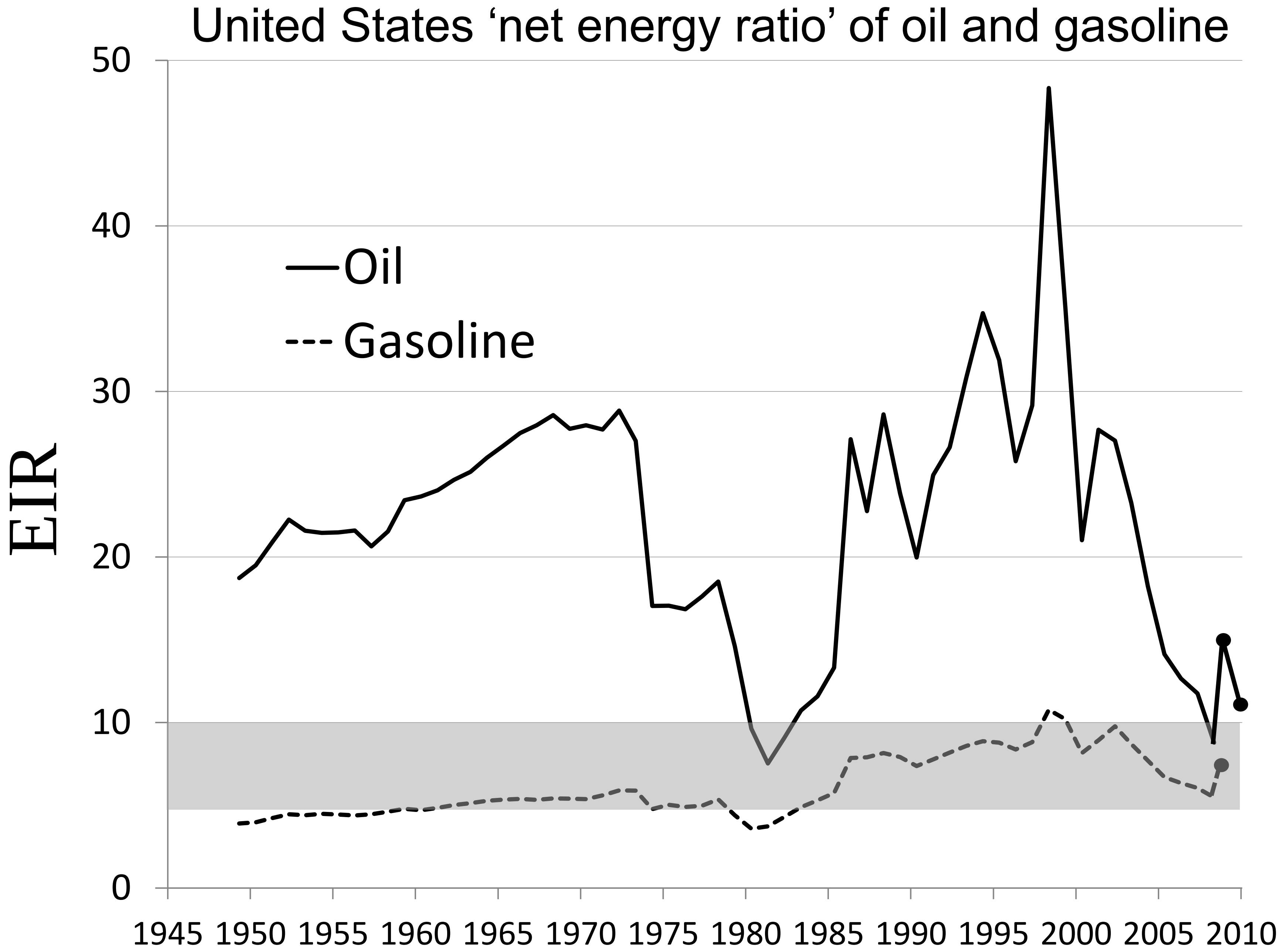
The Energy Intensity Ratio (EIR): a NER proxy using energy prices

- EIR = ("Btu/$" of fuel) / ("Btu/$" of economy) ~ E_{out}/E_{in}
  - "What is the cost of providing energy to the economy relative to the average productivity from consuming energy?"

- Example (using US 2008 values in $2008):
  - Oil at $100/BBL → 57,000 Btu/$2008
  - US economy: 6,960 Btu/$2008 GDP
  - $EIR_{oil,\ price}$ = 57,000/6,960 = 8.3



King, C. W. (2010) *Environmental Research Letters*. (EIA, AER for 2009 and 2010)



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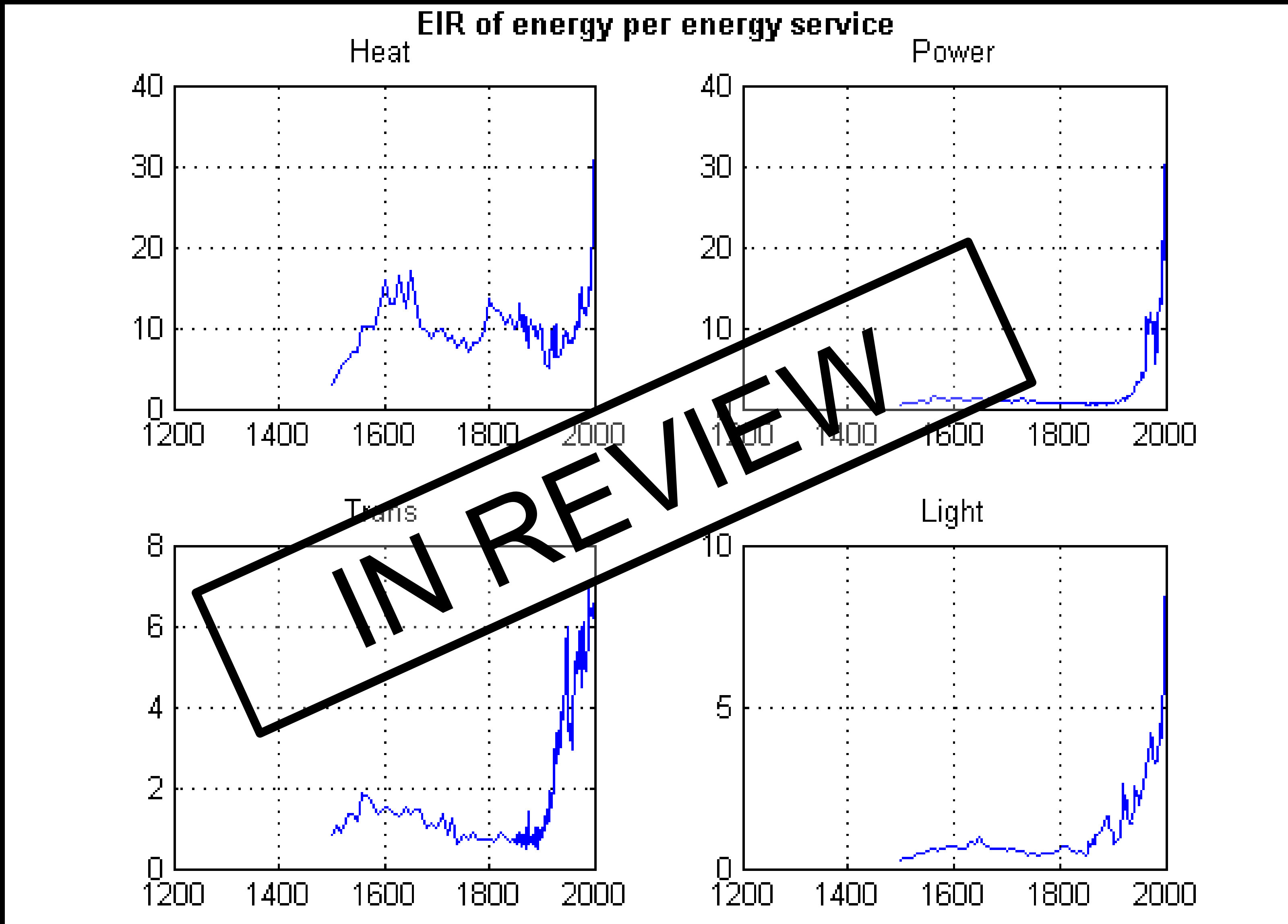
UK EIR based upon energy purchased per service

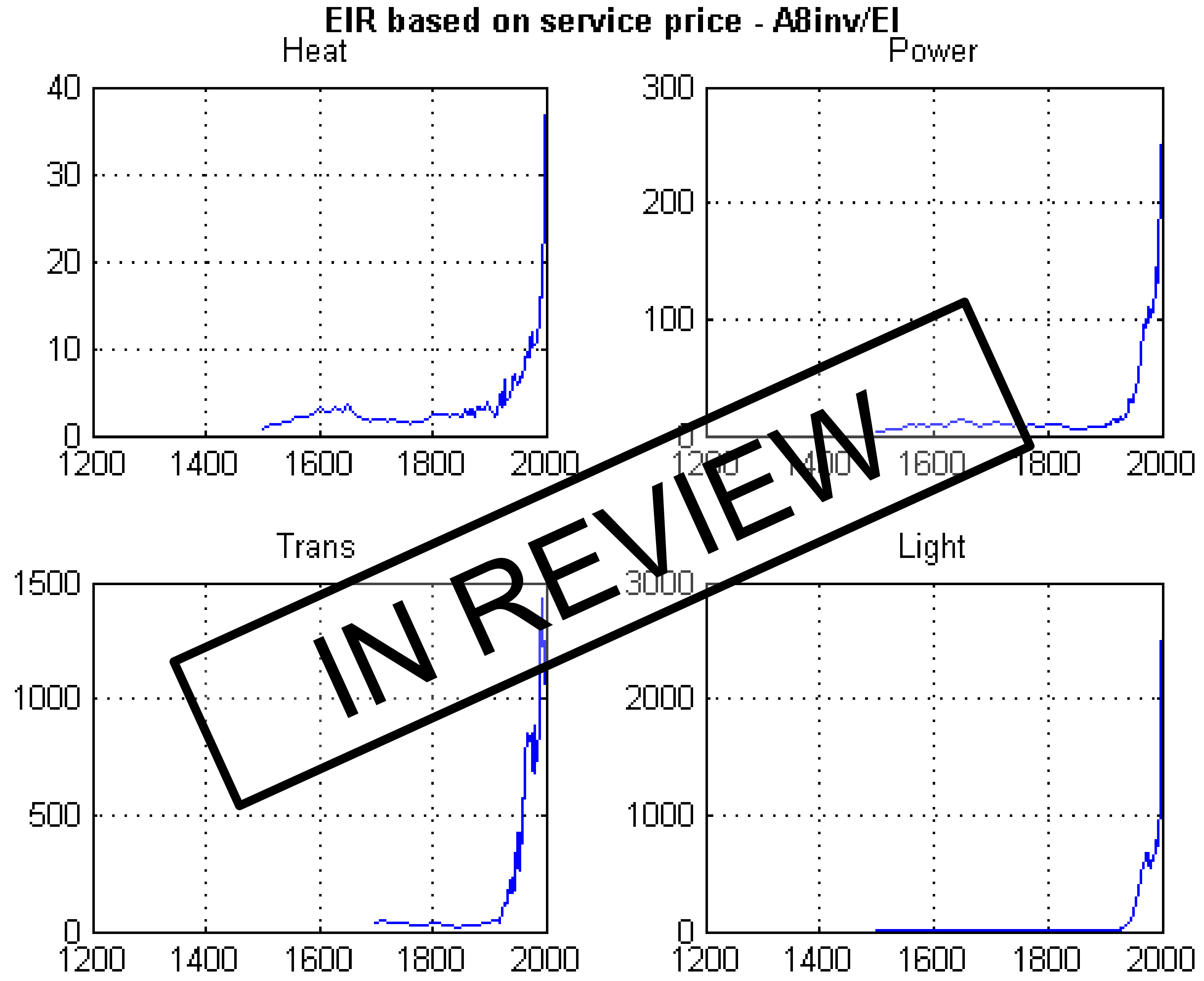


Data from Fouquet, R. (2008) *Heat, Power, and Light: Revolutions in Energy Services.*

UK EIR based upon energy service itself

- Transportation = [passenger·km/$] / [energy/GDP]
- Power = [energy/$] / [energy/GDP]
  - Power ~ useful work (animal work, electricity)
- Heat = [energy/$] / [energy/GDP]
- Light = [lumens/$] / [energy/GDP]

UK EIR based upon energy service itself



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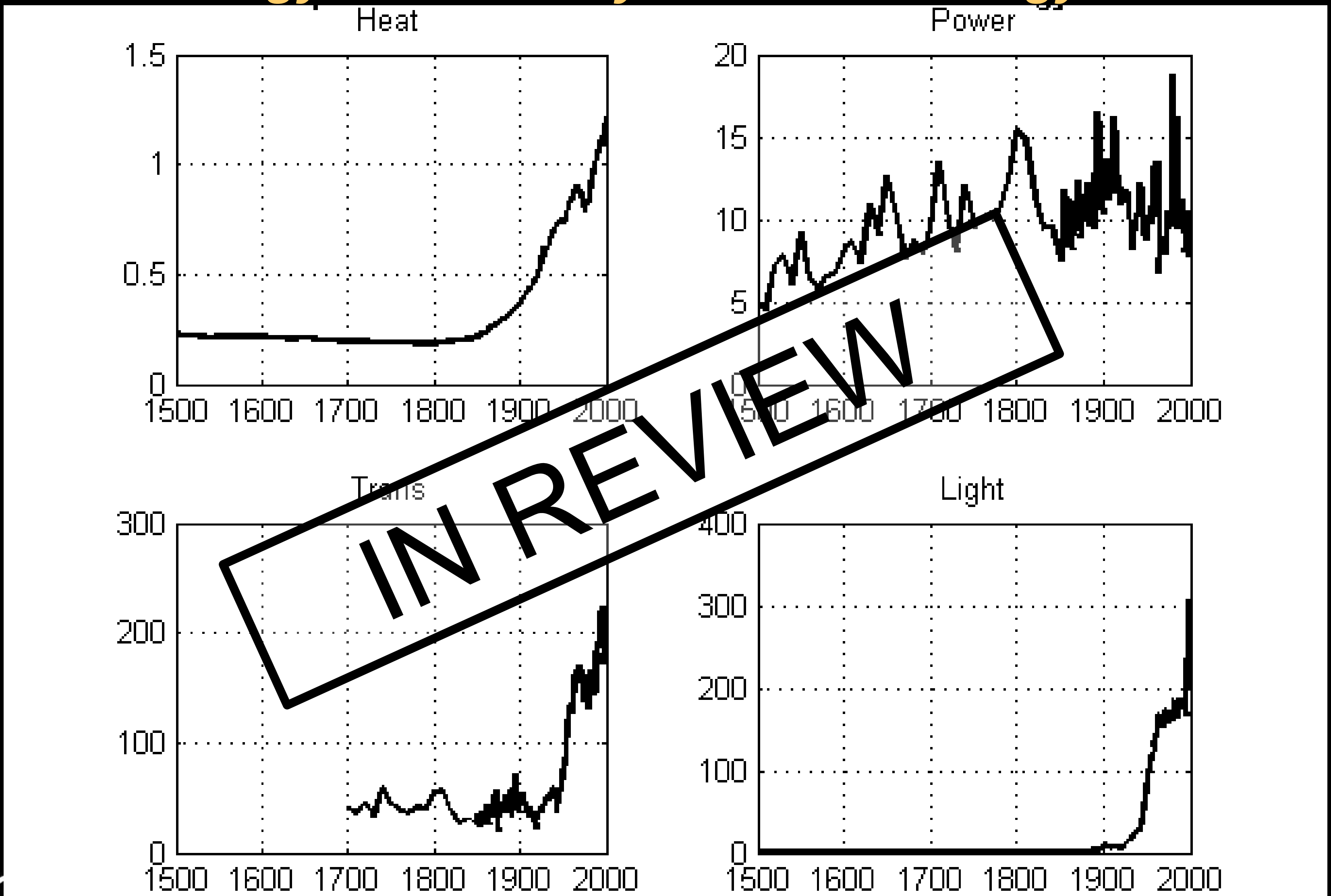
$EIR_{service}$ / EIR_{energy} = (£/energy) / (£/service)

increasing trend indicates benefits from investments in end-use technology & efficiency relative to energy investment



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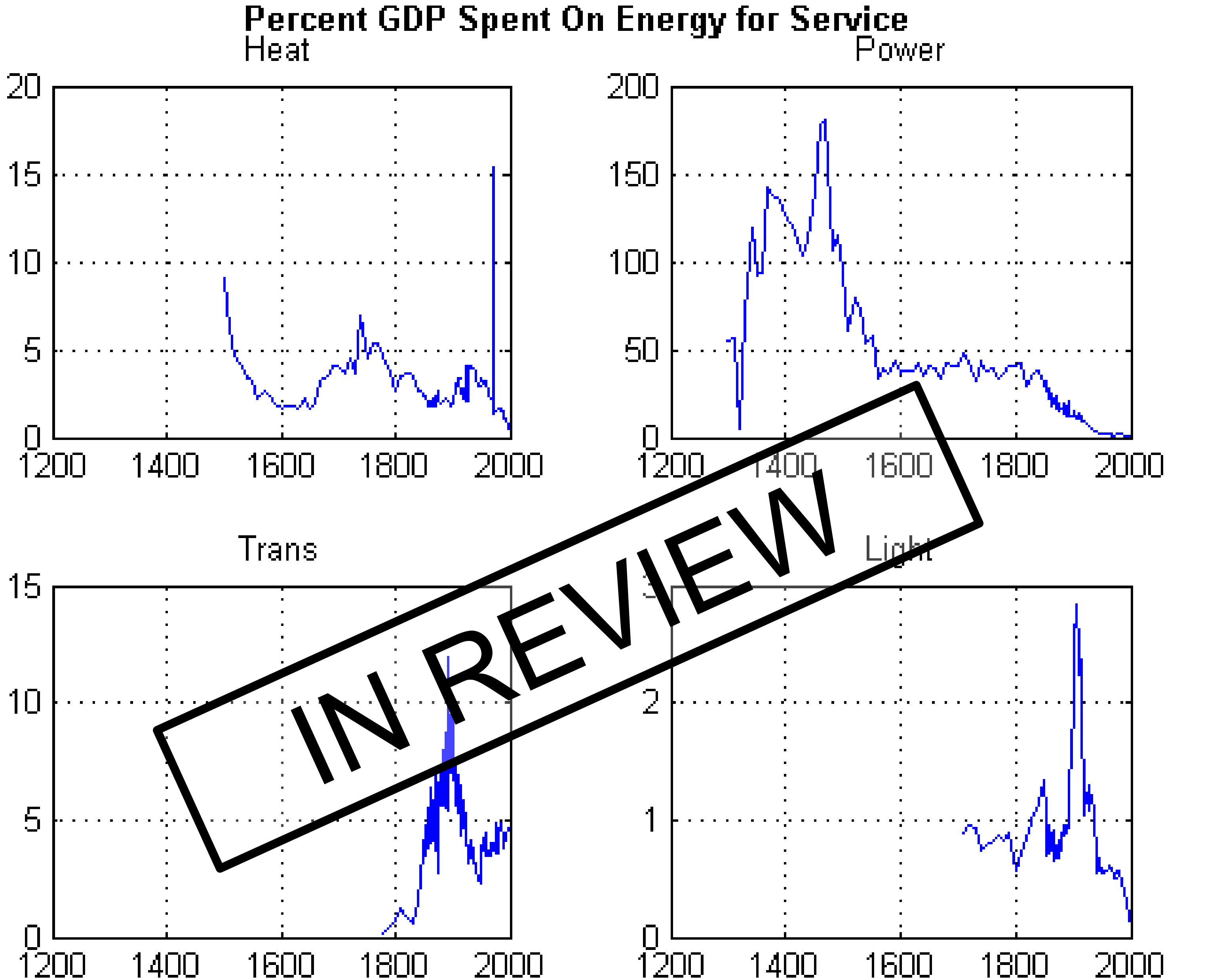

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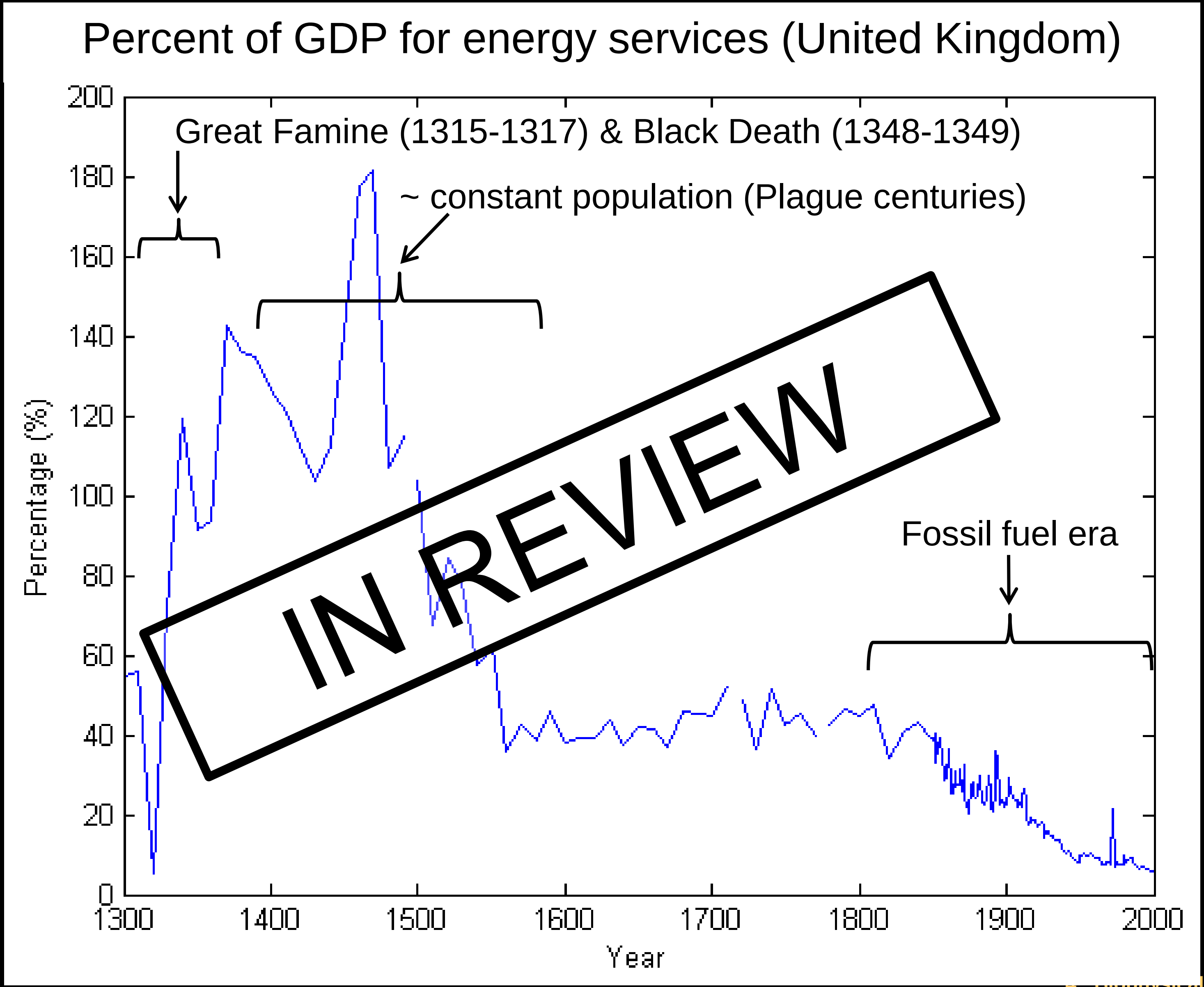
Energy and food expenditures have decreased for centuries



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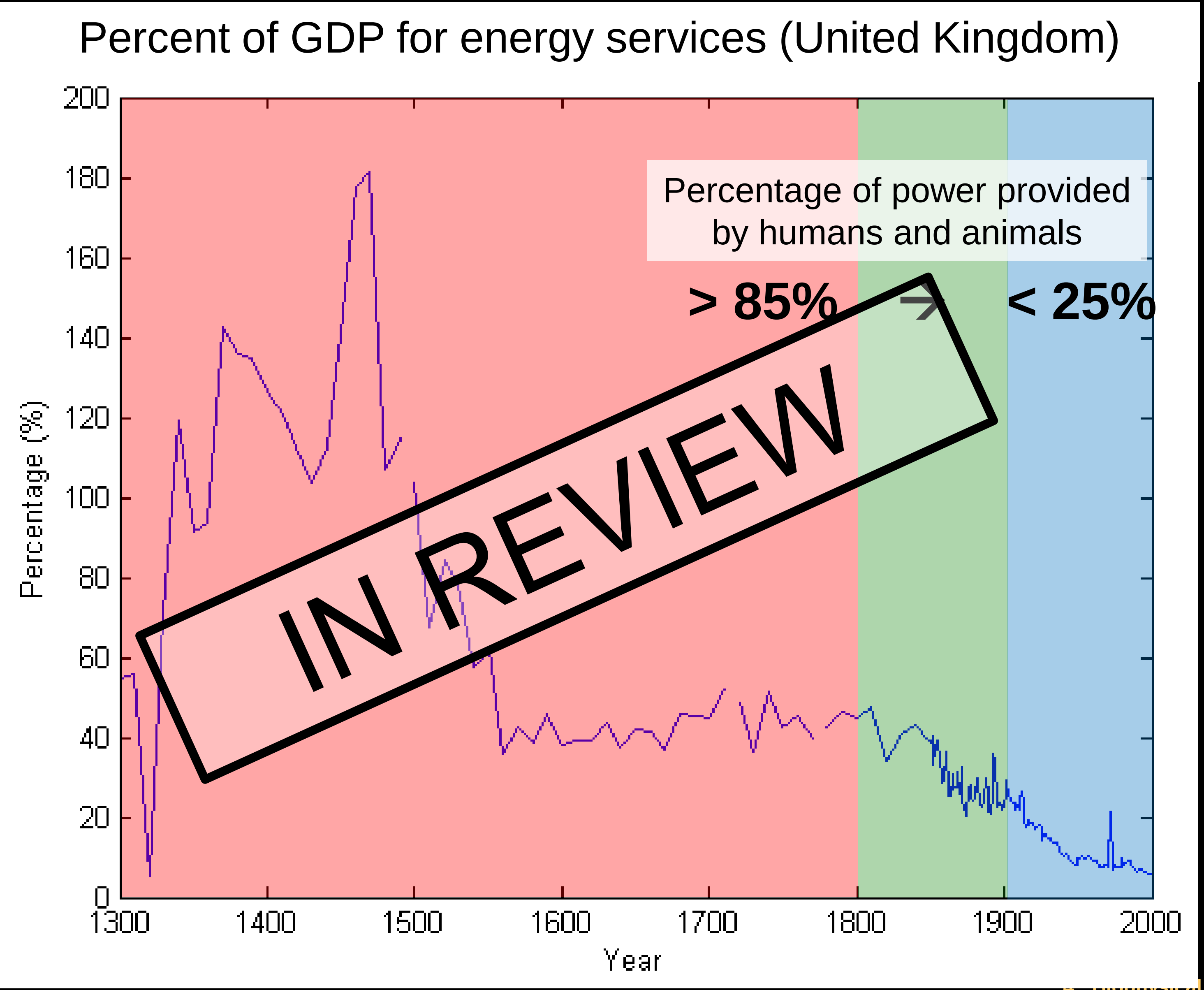
Food was the early energy supply …
for human and animal power



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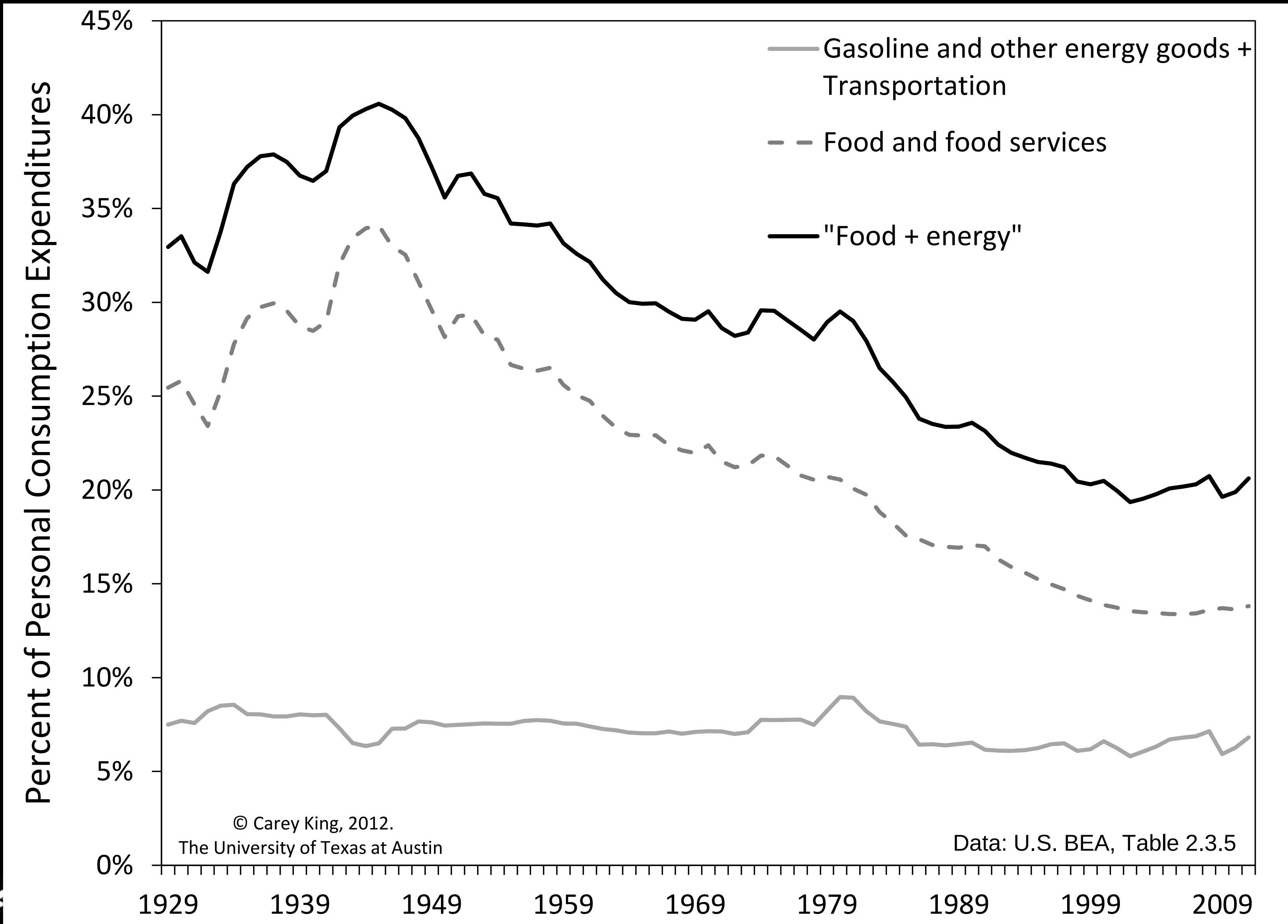
‘Food + energy’ expenditures are relevant for long-term analysis



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