The Income Share of Energy and Substitution: A Macroeconomic Approach

Nida Çakır Melek
Federal Reserve Bank of Kansas City

Musa Orak
Federal Reserve Board

August 24, 2022

ESEM 2022

Motivation

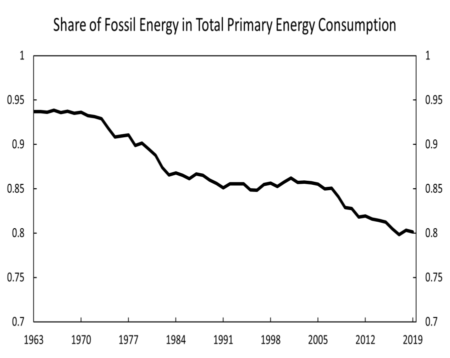
Addressing climate change and reducing emissions are at the forefront of all policy discussions around the world

- e.g. International Energy Agency: net-zero emissions by 2050, Assessment from the UN's Intergovernmental Panel on Climate Change

Goals require reducing an economy's use of fossil energy - coal, oil, natural gas - dramatically

Motivation

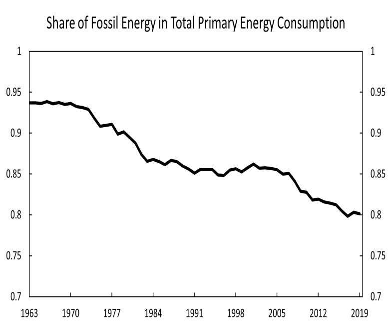
Fossil energy met 80 percent of U.S. total energy demand in 2019, about as high as a decade ago

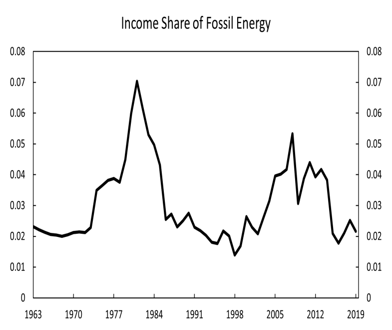


Motivation

Fossil energy met 80 percent of U.S. total energy demand in 2019, as high as a decade ago

U.S. income share of (fossil) energy -energy expenditures as a share of output- doesn't have an obvious trend





What do we do?

What can account for the changes in U.S. energy dependence measured by its factor share over 1963-2019?

- Provide a simple and explicit economic mechanism accounting for the historical trend in the income share of energy in terms of observable factor inputs
- Evaluate the roles of substitution elasticities
- Investigate whether we maintain consistency with other important characteristics of the U.S. economy
- What could be the implications of relatively higher energy prices as we phase out fossil fuels for the income share of energy and other factors of production?

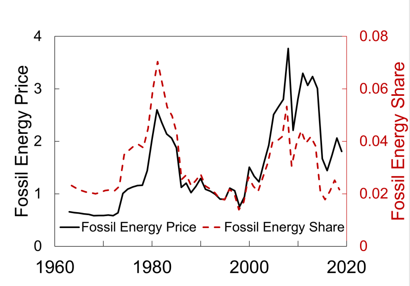
Findings

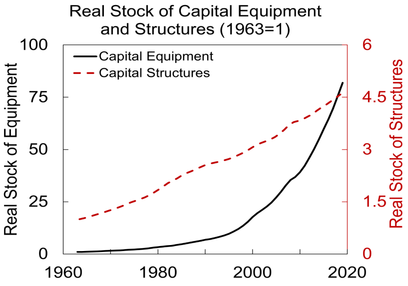
- With plausible differences in substitution elasticities, changes in observed factor inputs can account for the variation in the income share of energy from 1963 to 2019
- Capital-energy substitutability and energy-skill complementarity are important
  - Rapid growth in the stock of equipment capital seems to have prevented a larger share of U.S. income from being directed to energy
- Energy-saving technical change may simply be serving as a proxy for capital-energy substitutability
- Our model is also consistent with other important long-run U.S. growth observations
- Better and cheaper equipment capital can help reduce the economy's dependence on energy

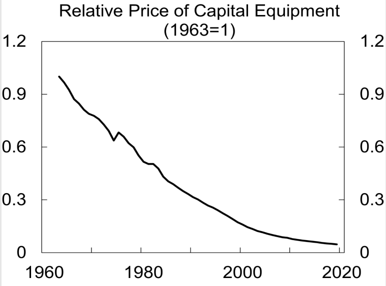
Literature

- Skill premium and skill-biased technical change/substitution (e.g. Katz and Murphy 1992 QJE; Krusell, Ohanian, Rios-Rull, Violante 2000 ECMA - KORV; Ohanian, Orak and Shen 2021)
- Directed technical change and U.S. energy dependence (e.g. Hassler, Krusell, and Olovsson 2021 JPE)
- Modeling energy demand (e.g. Berndt and Wood 1975 REStat; Atkeson and Kehoe 1999 AER)
- Climate integrated assessment models (e.g. Manne et al. 1995 EP; Hassler et al. 2020)

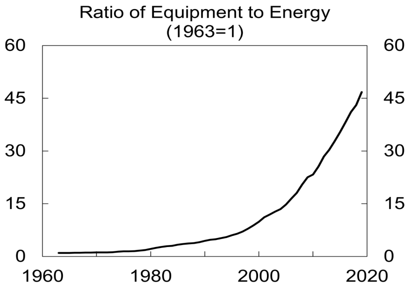
Features of the U.S. data

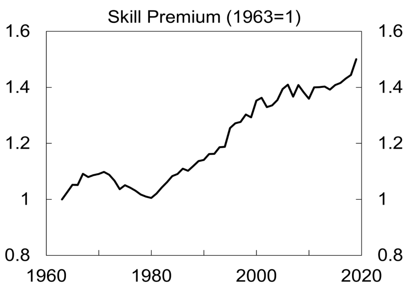






Features of the U.S. data





Summary

- no obvious trend in the income share of energy, which comoves positively with the price of energy
- rapid growth in equipment capital and a corresponding fall in its relative price
- a sharp rise in the ratio of equipment capital to energy
- a significant rise in the skill premium
- a decline in the income share of labor

Model

Build on KORV 2000

- abstract from the household sector, focus on the aggregate production
- develop a five-factor production function with different substitution elasticities
- given time series of quantities and the value of marginal product schedules, model yields factor prices
- compare the income share of energy predicted by the model with that in the data

Production Function

- Two types of capital: structural (K_s) and equipment (K_e)
- Two types of labor: unskilled (L_u) skilled (L_s)
- Energy: E

$$Y_t = A_t G_t = A_t K_{s,t}^{\alpha} \left(\mu L_{u,t}^{\sigma} + (1-\mu) \left(\lambda \left[\xi K_{e,t}^{\nu} + (1-\xi) E_t{}^{\nu} \right]^{\frac{\rho}{\nu}} + (1-\lambda) L_s^{\rho} \right)^{\frac{\sigma}{\rho}} \right)^{\frac{1-\alpha}{\sigma}}$$

where

$$L_{i,t} \quad = \quad e^{\varphi_{i,t}} h_{i,t} \qquad \forall i \in \{u, s\}$$

$\frac{1}{1-\nu}$: Elas. of subs. b/w K_{eq} and energy
$\frac{1}{1-\rho}$: Elas. of subst. b/w skilled labor and composite of K_{eq} and energy
$\frac{1}{1-\sigma}$: Elas. of subst. b/w unskilled labor and composite of K_{eq}, energy, skilled labor

Income share of energy

$$E_{share,t} = \frac{\lambda(1-\xi)}{(1-\lambda)} \left(\frac{E_t}{L_{s,t}}\right)^{\rho} L_{s_{share,t}} \left(\xi \left(\frac{K_{e,t}}{E_t}\right)^{\nu} + (1-\xi)\right)^{\frac{\rho-\nu}{\nu}}$$

which is based on income shares implied by the firm's first order conditions for hiring skilled labor and using energy

$\Longrightarrow$

$$\begin{aligned} g_{E_{share,t}} &\simeq \underbrace{\rho(g_{E,t} - g_{\varphi_{s,t}} - g_{h_{s,t}})}_{\text{relative quantity effect}} \\ &+ \underbrace{g_{L_{s_{share,t}}}}_{\text{energy-skill complementarity effect}} \\ &+ \underbrace{(\nu-\rho)\xi\Gamma\left(g_{E,t} - g_{K_e,t}\right)}_{\text{capital-energy substitutability effect}} \end{aligned}$$

▸ Experiments

Quantitative Analysis

We follow KORV's estimation methodology

1. Labor share:
$$\frac{w_{s,t}h_{s,t} + w_{u,t}h_{u,t}}{Y_t} = f_1(X_t, \varphi_t; \phi)$$
2. Wage-bill-ratio:
$$\frac{w_{s,t}h_{s,t}}{w_{u,t}h_{u,t}} = f_2(X_t, \varphi_t; \phi)$$
3. No-arbitrage condition:
$$\underbrace{A_{t+1}MP_{st,t+1} + (1-\delta_{st,t+1})}_{\text{expected return on str. capital}} = \underbrace{\frac{1}{p_t}A_{t+1}MP_{eq,t+1} + (1-\delta_{eq,t+1})E\left(\frac{p_{t+1}}{p_t}\right)}_{\text{expected return on equipment capital}}$$

stochastic elements:

$$\log(\varphi_{i,t}) = \log(\varphi_{i,0}) + \omega_{i,t}, i = s, u$$

$$(1-\delta_{eq,t+1})E\left(\frac{p_{t+1}}{p_t}\right) = (1-\delta_{eq,t+1})\frac{p_{t+1}}{p_t} + \varepsilon_t$$

Estimation

$X_t = \{K_{s,t}, K_{eq,t}, h_{u,t}, h_{s,t}, E_t\}$: set of inputs

$\phi = \{\delta_{str}, \delta_{eq}, \varphi_{s,0}, \sigma, \rho, \nu, \alpha, \mu, \lambda, \xi, \varphi_{u,0}, \sigma^2_{\varepsilon}, \eta^2_{\omega}\}$: set of parameters

We can reduce the number of parameters that we estimate by calibrating some of them.

Calibrated Parameters:

Parameter	**Value**	**Definition**	**Source**
δ_s	time dependent	Depr. of str. capital	BEA Tables
δ_e	time dependent	Depr. of eq. capital	BEA Tables
$\varphi_{s,0}$	2	Mean efficiency of skilled labor	Normalization
σ^2_{ε}	0.0233^2	Var. of the forecast error for p_{eq}	ARIMA estimation

Estimating ν

$$Y_t = A_t K_{s,t}^{\alpha} \left(\mu L_{u,t}^{\sigma} + (1-\mu) \left(\lambda \left[\xi K_{e,t}^{\nu} + (1-\xi) E_t^{\nu} \right]^{\frac{\rho}{\nu}} + (1-\lambda) L_s^{\rho} \right)^{\frac{\sigma}{\rho}} \right)^{\frac{1-\alpha}{\sigma}}$$

FOCs yield

$$\frac{r_{e,t} K_{e,t}}{p_{E,t} E_t} = \frac{\xi}{1-\xi} \left(\frac{K_{e,t}}{E_t} \right)^{\nu}$$

Taking the log of both sides

$$\log \frac{r_{e,t} K_{e,t}}{p_{E,t} E_t} = \log \frac{\xi}{1-\xi} + \nu \log \frac{K_{e,t}}{E_t}$$

and running a regression would give $\xi = 0.7977$ and $\nu = 0.1011$

$\Longrightarrow$ a slightly more substitutibility between K_e and E than the Cobb-Douglass case

Rest of the Parameters to be Estimated

$\frac{1}{1-\sigma}$	Elasticity of subst. b/w unskilled labor and composite of K_e, E, and skilled labor
$\frac{1}{1-\rho}$	Elasticity of subst. b/w skilled labor and composite of K_e and E
μ	Share of unskilled labor in outer CES
$1-\lambda$	Share of skilled labor in second inner CES
α	Share of structures capital
$\varphi_{u,0}$	Mean efficiency of unskilled labor
η_ω^2	Variance of the labor efficiency shocks

Other elasticities of Substitution

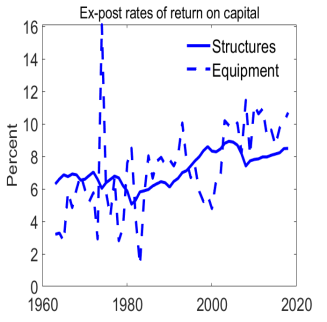
$$Y_t = A_t K_{s,t}^{\alpha} \left(\mu L_{u,t}^{\sigma} + (1-\mu) \left(\lambda \left[\xi K_{e,t}^{\nu} + (1-\xi) E_t^{\nu} \right]^{\frac{\rho}{\nu}} + (1-\lambda) L_s^{\rho} \right)^{\frac{\sigma}{\rho}} \right)^{\frac{1-\alpha}{\sigma}}$$

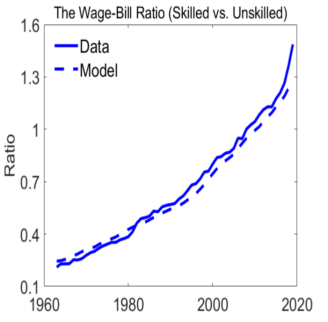
Table: Parameter Estimates, Baseline

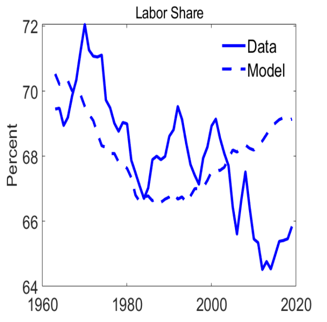
	σ	ρ	α	η_ω	ν
Value	0.437	−0.389	0.090	0.241	0.101
(Std. Error)	(0.031)	(0.044)	(0.002)	(0.055)	(0.049)

They imply energy-skill complementarity ($\rho < 0$) and capital-energy substitutability ($\nu > \rho$)

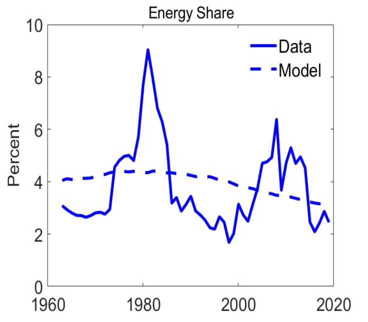
Model Fit


Ex-post rates of return on capital
Structures
Equipment
Percent
0
2
4
6
8
10
12
14
16
1960
1980
2000
2020

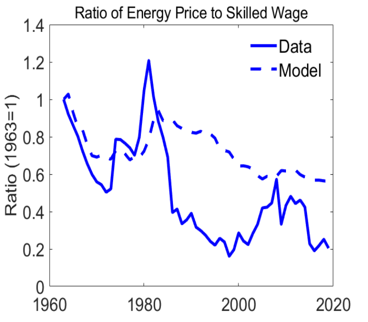

The Wage-Bill Ratio (Skilled vs. Unskilled)
Data
Model
Ratio
0.1
0.4
0.7
1
1.3
1.6
1960
1980
2000
2020


Labor Share
Data
Model
Percent
64
66
68
70
72
1960
1980
2000
2020

Model Fit



Energy Share
Percent
10
8
6
4
2
0
1960
1980
2000
2020
Data
Model

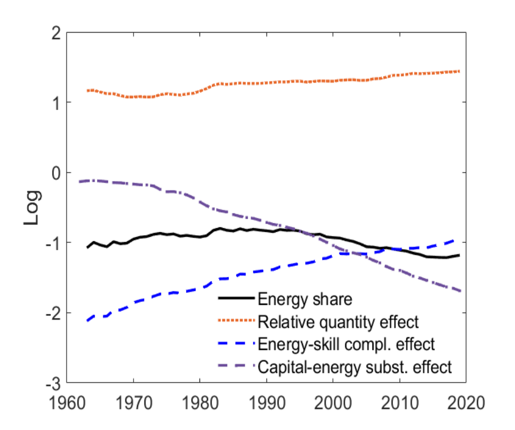


Ratio of Energy Price to Skilled Wage
Ratio (1963=1)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1960
1980
2000
2020
Data
Model

Decomposition of the benchmark model's energy share

$$\log E_{share,t} \simeq \underbrace{\rho\left[\log E_t - \log L_{s,t}\right]}_{\text{relative quantity effect}} + \underbrace{\frac{\rho-\nu}{\nu}\log\left[\xi\left(\frac{K_{e,t}}{E_t}\right)^{\nu} + (1-\xi)\right]}_{\text{capital-energy subst. effect}}$$

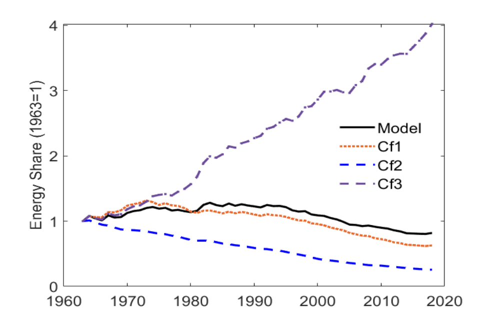
$$+ \underbrace{\log L_{s_{share,t}}}_{\text{energy-skill compl. effect}}$$



Counterfactuals

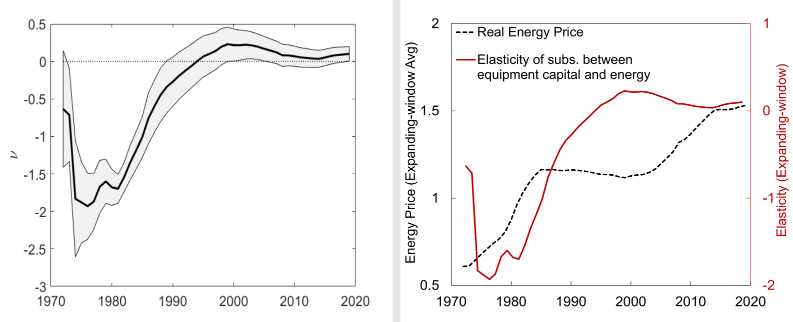
$$g_{E_{share,t}} \simeq \underbrace{\rho\left(g_{E,t} - g_{\varphi_{s,t}} - g_{h_{s,t}}\right)}_{\text{relative quantity effect}} + \underbrace{g_{L_{s_{share,t}}}}_{\text{energy-skill compl. effect}} + \underbrace{(\nu - \rho)\xi\Gamma\left(g_{E,t} - g_{K_e,t}\right)}_{\text{capital-energy subst. effect}}$$

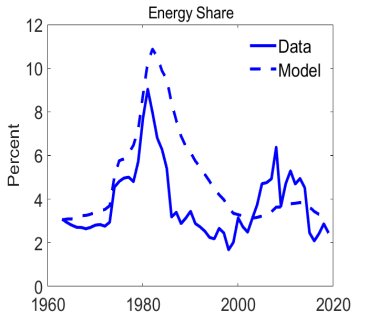
- **Cf1:** Energy input and skilled labor input grow at the same rate
- **Cf2:** Skilled labor share remains unchanged at its 1963 level
- **Cf3:** Equipment capital and energy input grow at the same rate

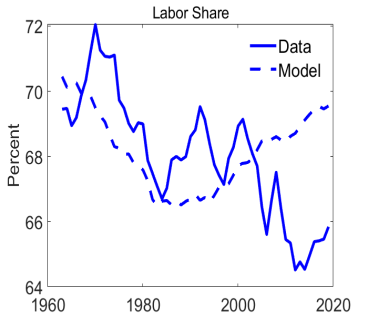


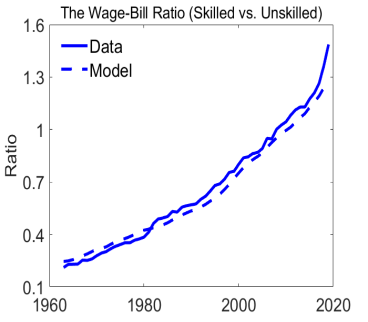
Accounting for short-run movements in the income share of energy: time-varying elasticity

$$\log \frac{r_{e,t} K_{e,t}}{p_{E,t} E_t} = \log \frac{\xi}{1-\xi} + \nu \log \frac{K_{e,t}}{E_t}$$




Energy Share
Percent
12
10
8
6
4
2
0
1960
1980
2000
2020
Data
Model


Labor Share
Percent
72
70
68
66
64
1960
1980
2000
2020
Data
Model

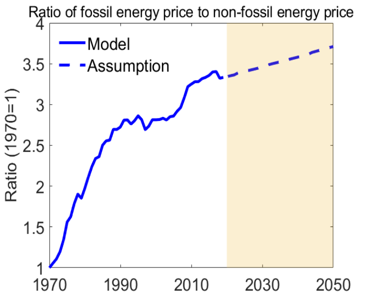

The Wage-Bill Ratio (Skilled vs. Unskilled)
Ratio
1.6
1.3
1
0.7
0.4
0.1
1960
1980
2000
2020
Data
Model

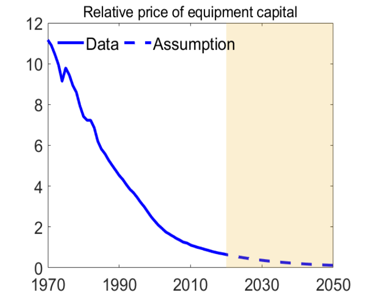
Alternative energy sources and implications of higher relative energy prices

Estimate the model with six-factors of production including non-fossil energy

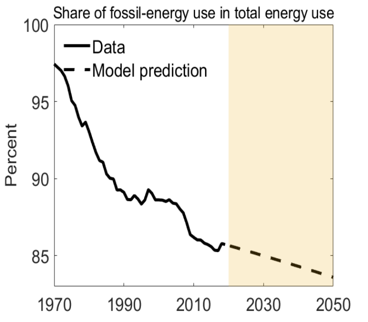
- We find that fossil and non-fossil energy are substitutable, with an elasticity of substitution of 1.53

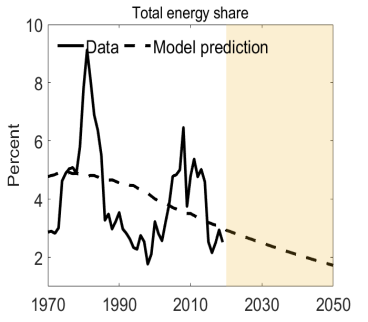
Prediction exercise:





Model predictions for future energy use and income share of energy





Concluding Remarks

- Capital-energy substitutability and energy-skill complementarity are important in understanding the long-run trend in the U.S. income share of energy
- Varying substitution between equipment capital and energy helps account for the movements in the income share of energy
  - energy-saving technical change may simply be serving as a proxy for capital-energy substitutability
- Providing inputs for macro-climate studies
- When designing policies to alleviate U.S. energy dependence, the interaction between all factors of production, particularly between capital-energy services and skilled labor, should be taken into account
  - Better and cheaper equipment capital and increased training/education can help reduce the economy's dependence on fossil energy

Estimated Parameters with an Alternative Target

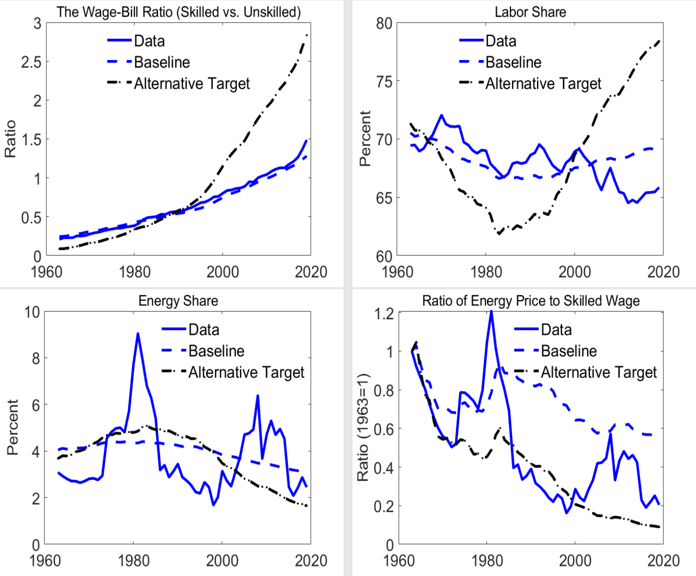
Targets used:

1. Baseline: no-arbitrage, wbr, labor share
2. Alternative: no-arbitrage, wbr, energy share

Table: Parameters estimated for the 1963–2019 period

	σ	ρ	ν	α
Baseline	0.437	-0.389	0.101	0.090
Alternative	0.828	-1.126	0.101	0.100

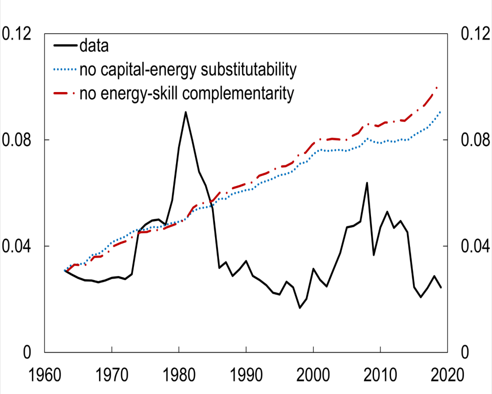
Model Fit with the Alternative Target



An initial exploration of the Importance of Substitution (1)

What would have happened to the energy share between 1963 and 2019 if there were no capital-energy substitutability?

$$Y_t = K_{e,t}^{\alpha}\left[\lambda E_t^{\epsilon} + (1-\lambda)L_{s,t}^{\epsilon}\right]^{\frac{1-\alpha}{\epsilon}}$$

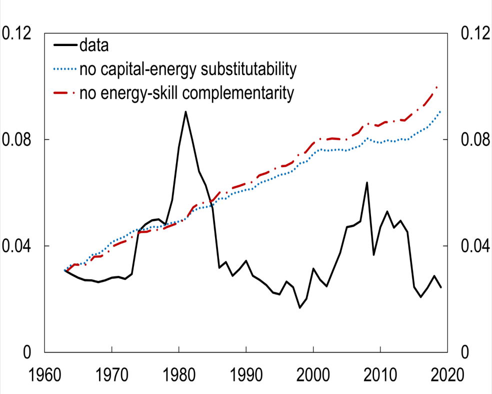


back

An initial exploration of the Importance of Substitution (2)

What would have happened to the energy share between 1963 and 2019 if there were no energy-skill complementarity?

$$Y_t = L_{s,t}^{\alpha_1}\left[\lambda_1 E_t^{\epsilon_1} + (1-\lambda_1)K_{e,t}^{\epsilon_1}\right]^{\frac{1-\alpha_1}{\epsilon_1}}$$



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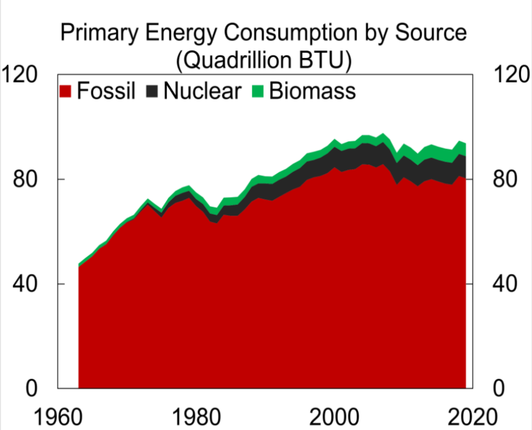
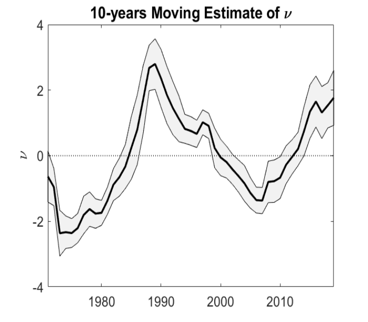
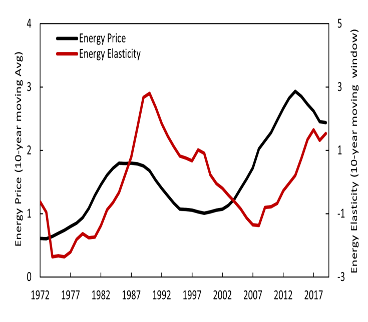


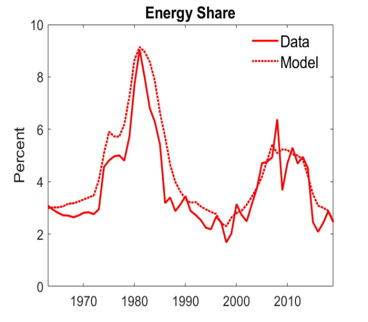
Primary Energy Consumption by Source
(Quadrillion BTU)
Fossil
Nuclear
Biomass
120
80
40
0
1960
1980
2000
2020

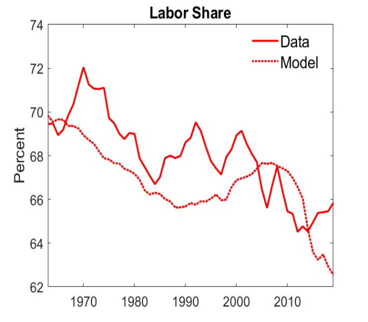
back

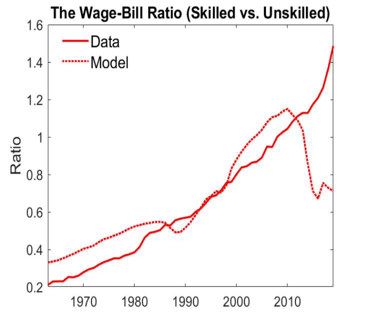
10-year window rolling estimation






Energy Share
Percent
10
8
6
4
2
0
1970
1980
1990
2000
2010
Data
Model


Labor Share
Percent
74
72
70
68
66
64
62
1970
1980
1990
2000
2010
Data
Model


The Wage-Bill Ratio (Skilled vs. Unskilled)
Ratio
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
1970
1980
1990
2000
2010
Data
Model

Energy Data

Sources: EIA, Monthly and Annual Energy Reviews, 1949-2019

Energy Use (E_t): energy use is in units of BTU, constructed using consumption data for petroleum products, natural gas, coal and their respective heat contents from the EIA

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Capital Stock Data

Sources: BEA NIPA tables, DiCecio (2009) FRED, Krusell et al. (2000), Gordon (1990)

- nonresidential structures investment
- investment in nonresidential equipment capital and intellectual property products

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Labor Input and Wages

- Person level data excluding: self employed, unpaid family workers and gricultural and military workers.
- Dropped: less than 260 hours and lower than half the minimum wage.
- Consistent topcoding for post-1975: Income Component Rank Proximity Swap ethod.
- 264 groups by: age, sex, race and education.
- Aggregation into two skill group: skilled vs unskilled.
- CPS sampling weights are used.

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Labor and Capital Shares

- Capital share: BEA NIPA
  - Labor income (LI)
  - Capital income (CI): depreciation + corporate profits + net interest + rental income of people

  $$\text{aggregate capital share} = \frac{CI}{LI+CI}$$

- share of labor = 1 - aggregate capital share - energy share
- share of equipment capital = aggregate capital share - α

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