Climate Protection Potentials of Digitalized Production Processes: Microeconometric Evidence?

Part of the research project CliDiTrans, funded by the German Federal Ministry of Education and Research

Janna Axenbeck [1,2] Thomas Niebel [1]

[1]ZEW Mannheim, Digital Economy Department

[2]Justus-Liebig-University Giessen, Faculty of Economics

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Motivation

- Decline in industrial energy intensity improvement growth.

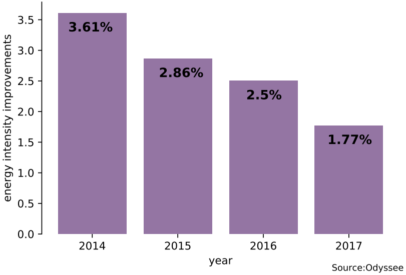

Figure 1: Energy intensity improvement per year within the European industry

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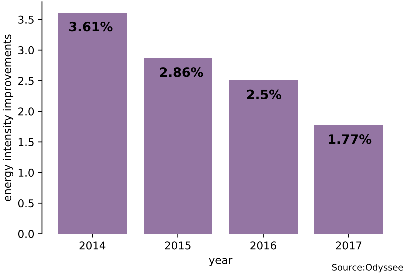

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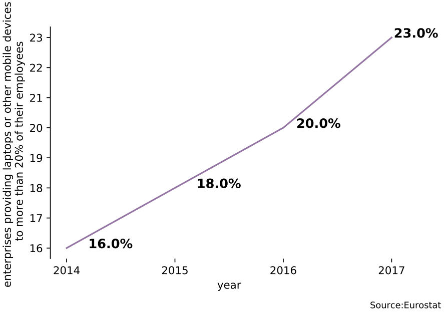

Figure 2: Share of European manufacturing firms providing portable devices to more than 20% of their employees

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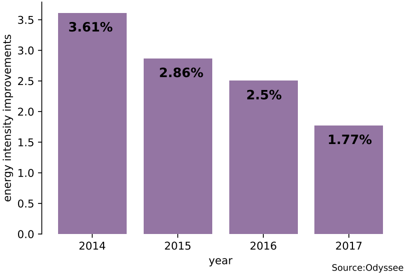

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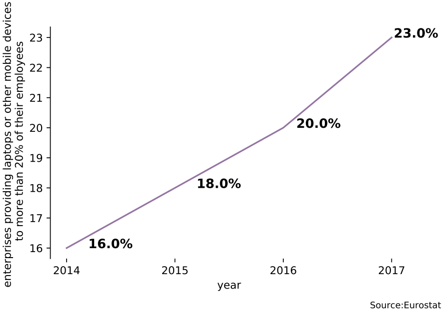

Figure 2: Share of European manufacturing firms providing portable devices to more than 20% of their employees

How do digitalization and firm-level energy efficiency improvements relate to each other?

ICT and Energy Efficiency

- ICT improve the quantity and quality of information (e.g., smart manufacturing) and thus increase (energy) efficiency.
- Previous sector-level studies find a (strong) positive link between ICT usage and (electric) energy efficiency improvements (Collard et al. 2005, Bernstein & Madlener 2010, Schulte et al. 2016) as well as a decrease in carbon emissions (Kopp & Lange 2019).

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  - A **1%** increase in ICT capital decreases energy intensity by **0.235%**, **ICT capital grows at 12%** per year (Schulte et al. 2016).

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- **Can findings be confirmed at the firm level and do heterogeneous effects exist?**

Data

AFiD (Amtliche Firmendaten für Deutschland) 2009-2017: Unbalanced panel data from the German Statistical Offices on manufacturing firms

- Reporting is obligatory, data is thoroughly checked
- Approx. 13,800 firms per year
- Variables:
  - Energy use & costs
  - Software investments
  - Control variables

Additionally, gross value added deflators (Eurostat) and EU KLEMS data.

Software capital as a proxy for ICT capital

- Perpetual inventory method ($K_t = (1-\delta)K_{t-1} + I_t$)
- Sufficient proxy for ICT usage?
  - Analysis conducted on a sub-sample (approx. 16,000 observations, 2012-2017)

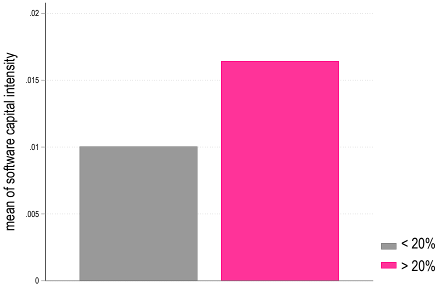

Figure 3: Software capital intensity by firms that do and do not provide portable devices to >20% of employees

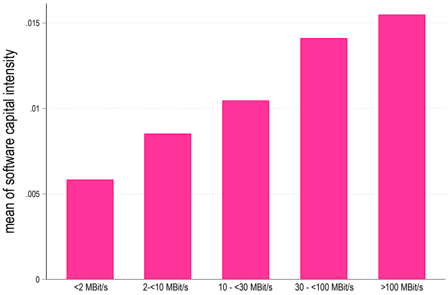

Figure 4: Software capital intensity by maximum data transmission rate

- heavily skewed and lumpy, 20% of firms without any software investments.

Source: Source: AFiD; Own calculation

Empirical Strategy

- Translog cost function (Christensen et al. 1973, Berndt & Wood 1975, Brown & Christensen 1981, Berndt & Hesse 1986, Schulte et al. 2016)[1]
- Forms of capital considered as quasi-fixed factors, materials as weakly separable
- Empirical specification (first differences):

$$\Delta S_{Eit} = \beta_{EE} \Delta ln(\frac{P_E}{P_L})_{it} + \beta_{EK_{ICT}} \Delta ln(\frac{K_{ICT}}{Y})_{it} + \beta_{EK_N} \Delta ln(\frac{K_N}{Y})_{it} + \beta^*_{EY} \Delta ln Y_{it} + \delta_{Eti} t_{it} + \Delta u_{it} \quad (1)$$

- Demand elasticity:

$$\epsilon_{EK_{ICT}} = \frac{\partial \ln(E/Y)}{\partial \ln K_{ICT}} = \frac{\beta_{EK_{ICT}}}{S_E} - S_{K_{ICT}} \quad (2)$$

S_E: share of energy costs in variable costs; P_E: price for energy; P_L: price for labour; K_{ICT}: ICT capital stock; K_N: non-ICT capital stock; Y: output; t: time dummies.

[1] Including symmetry ($\beta_{EL} = -\beta_{EE}$) and summarizing $\beta_{EY*} = \beta_{EY} + \beta_{EK_{ICT}} + \beta_{EK_N}$

Results

Table 1: First difference estimation results.

	(1)	(2)	(3)	(4)		(5)
	FD	$K_{ICT,t-1} > 0$	$t > 3$	$K_{ICT}(\uparrow)$		POLS
$\triangle S_E$					S_E	
$\triangle \ln(\frac{P_E}{P_L})$	0.0289***	0.0273***	0.0302***	0.0252***	$\ln(\frac{P_E}{P_L})$	-0.00358***
	(49.89)	(38.73)	(38.78)	(30.35)		(-3.88)
$\triangle \ln(\frac{K_{ICT}}{Y})$	-0.000246***	-0.000429**	-0.000209***	-0.000196***	$\ln(\frac{K_{ICT}}{Y})$	-0.00105***
	(-5.33)	(-2.70)	(-4.56)	(-3.80)		(-10.31)
$\triangle \ln(\frac{K_N}{Y})$	-0.00120***	-0.00156**	-0.00100*	-0.000767	$\ln(\frac{K_N}{Y})$	0.00902***
	(-3.47)	(-3.20)	(-2.15)	(-1.01)		(18.95)
$\triangle \ln(Y)$	0.00199***	0.00193*	0.00185*	0.00174	$\ln(Y)$	0.00929***
	(3.44)	(2.56)	(2.21)	(1.73)		(22.65)
Year	x	x	x	x		x
Economic sector	x	x	x	x		x
Multi-unit	x	x	x	x		x
Federal state	x	x	x	x		x
Size class	x	x	x	x		x
EEG exemption	x	x	x	x		x
Producer	x	x	x	x		x
Observations	90179	63663	59594	25600		124057
Adj. R^2	0.262	0.247	0.286	0.246		0.740
ϵEK_{ICT}	-0.007***	-0.011**	-0.007***	-0.010***		-0.0167***

t statistics in parentheses. First-difference estimation. Clustered standard errors. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

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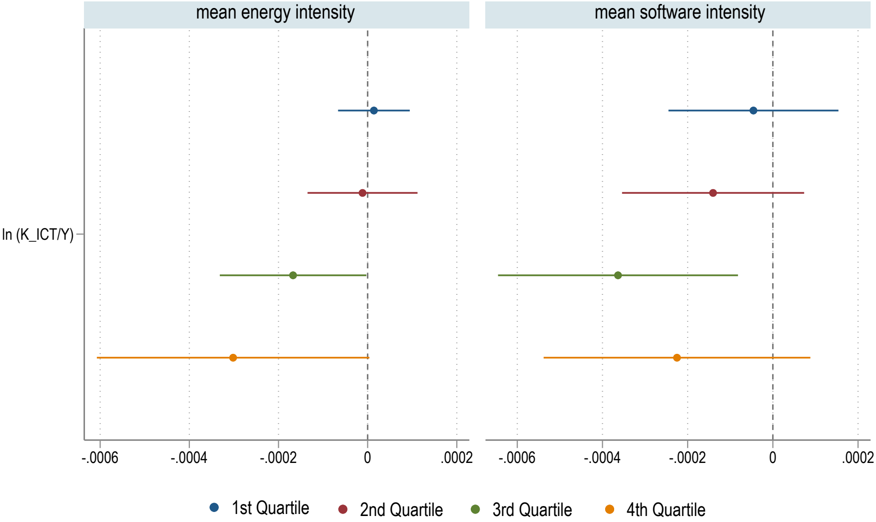
Results: Heterogeneous Effects

- Sample is split into quartiles, fixed effects, zero software capital stocks are excluded from the analysis of software intensity



Results: ICT Intensity

Selection of variables based on a CES production (Bernstein & Madlener 2010, Collard et al. 2005)

$$\Delta ln\left(\frac{E}{Y}\right)_{it} = \Delta\beta_{\frac{P_E}{P_{PPI}}} ln\left(\frac{P_E}{P_{PPI}}\right)_{it} + \Delta\beta_{\frac{K_{ICT}}{K_N}} ln\left(\frac{K_{ICT}}{K_N}\right)_{it} + \delta_{Eti} t_{it} + \Delta u_{it} \tag{3}$$

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Table 2: First difference estimation results.

	(1)	(2)	(3)
	FD	$K_{ICT,t-1}$ >0	$K_{ICT}(\uparrow)$
$\triangle$ ln($\frac{P_E}{P_{PPI}}$)	-0.447***	-0.464***	-0.483***
	(-57.66)	(-49.44)	(-33.31)
$\triangle$ ln($\frac{K_{ICT}}{K_N}$)	-0.00273***	-0.00488*	-0.00255**
	(-3.63)	(-2.43)	(-2.95)
Year	x	x	x
Economic sector	x	x	x
Multi-unit	x	x	x
Federal state	x	x	x
Size class	x	x	x
EEG exemption	x	x	x
Producer	x	x	x
Observations	89790	64693	25495
Adj. R^2	0.226	0.230	0.252

t statistics in parentheses. First-difference estimation. Clustered standard errors.* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Conclusion

- **An increase in software capital intensity is significantly associated with a decrease in energy intensity at the firm level**
  - Effects are not large enough to substantially improve energy efficiency
- Moreover:
  - Effects appear to be larger for firms with high energy intensity
  - Results indicate that the link is larger *between* than *within* firms

Thank you for your attention!

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Theoretical Model (Schulte et al. 2016)

Translog cost function approach (twice differentiable, linearly homogeneous and concave in factor prices)[2]

$$VC = P_E E + P_L L \tag{4}$$

$$VC = f(P_E, P_L, K_{ICT}, K_N, Y, t) \tag{5}$$

$$\begin{aligned} lnVC = & \beta_0 + \beta_Y lnY + \frac{1}{2}\beta_{YY} ln(Y)^2 + \beta_T t + \frac{1}{2}\beta_{TT} t^2 + \sum_k \beta_k lnP_k + \sum_m \beta_{K_m} lnK_m \\ & + \frac{1}{2}\sum_k \sum_l \beta_{kl} lnP_k lnP_l + \frac{1}{2}\sum_m \sum_n \beta_{K_m K_n} lnK_m lnK_n + \sum_k \beta_{kY} lnP_k lnY \\ & + \sum_m \beta_{K_m Y} lnK_m lnY + \sum_k \sum_m \beta_{kK_m} lnP_k lnK_m + \sum_k \delta_{kT} lnP_k t \\ & + \sum_m \delta_{K_m T} lnK_m t + \delta_{YT} lnYt \end{aligned} \tag{6}$$

with $k, l \in \{E, L\}$; $m, n \in \{ICT, N\}$.

[2] Materials are assumed to be weakly separable.

Demand Elasticities (Schulte et al. 2016)

$$\epsilon_{jK_{ICT}} = \frac{\partial \ln j}{\partial \ln K_{ICT}} = \frac{\partial \ln \frac{S_j VC}{P_j}}{\partial \ln K_{ICT}} = \frac{\partial \ln S_j}{\partial \ln K_{ICT}} + \frac{\partial \ln VC}{\partial \ln K_{ICT}} - \frac{\partial \ln P_j}{\partial \ln K_{ICT}} \tag{7}$$

Assuming exogenous prices (which implies $\frac{\partial \ln P_j}{\partial \ln K_{ICT}} = 0$):

$$\epsilon_{jK_{ICT}} = \frac{\partial \ln S_j}{\partial \ln K_{ICT}} + \frac{\partial \ln VC}{\partial \ln K_{ICT}} - 0 = \frac{\beta_{jK_{ICT}}}{S_j} + \frac{\partial VC}{\partial K_{ICT}} \frac{K_{ICT}}{VC} \tag{8}$$

$$\epsilon_{jK_{ICT}} = \frac{\beta_{jK_{ICT}}}{S_j} - \frac{R_{K_{ICT}} K_{ICT}}{VC} \tag{9}$$

$$\epsilon_{jK_{ICT}} = \frac{\beta_{jK_{ICT}}}{S_j} - S_{K_{ICT}} \tag{10}$$

Results from Schulte et al. (2016)

Table 3: Main Results - Schulte et al. (2016)

Dependent variable:	$\triangle S_E$ (1)	$\triangle S_E$ (2)	$\triangle S_E$ (3)	$\triangle S_{ELEC}$ (4)	$\triangle S_{NELEC}$ (5)
$\triangle \ln(\frac{P_E}{P_L})$	0.049***	0.048***	0.047***		
	(9.08)	(8.97)	(8.62)		
$\triangle \ln(\frac{P_{NELEC}}{P_L})$				-0.001*	0.035***
				(-1.74)	(30.16)
$\triangle \ln(\frac{P_{ELEC}}{P_L})$				0.020***	-0.001***
				(28.55)	(-1.74)
$\triangle \ln(\frac{K_{ICT}}{Y})$	-0.010**	-0.014***	-0.016***	0.001	-0.009***
	(-3.08)	(-4.96)	(-6.01)	(0.76)	(-4.46)
$\triangle \ln(\frac{K_N}{Y})$	-0.019***	-0.004	0.009	-0.006***	-0.014***
	(-3.95)	(-0.51)	(1.03)	(-2.63)	(-2.97)
$\triangle \ln(Y)$	0.008	0.028*	0.041***	-0.000	0.008**
	(0.95)	(2.23)	(3.26)	(-0.03)	(1.97)
Control dummies					
Year	x	x	x	x	x
Country x industry			x		
Country DVs		x			
Industry DVs		x			
Observations	2,889	2,889	2,889	2,889	2,889
Adjusted R^2	0.352	0.372	0.350	0.30	0.33

Energy Carriers over Time

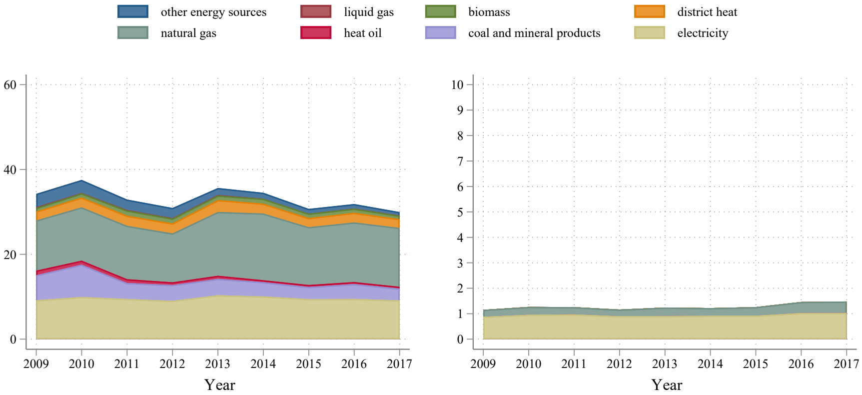


Figure 5: Mean (left) & median (right) use of different energy sources per year.

Source: Source: AFiD; Own calculation

Mean & Median of Selected Variables over Time

- Software capital increases whereas other inputs decrease

Figure 6: Percentage change of mean (non-) software capital, labor and energy use divided by output (base year 2009).

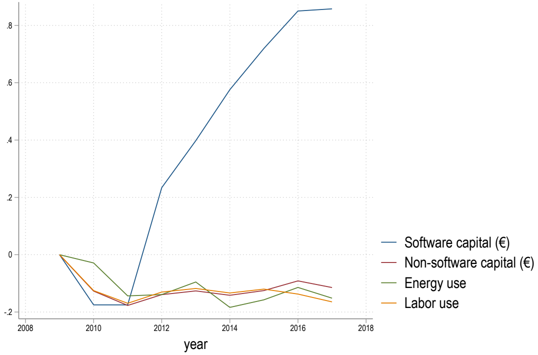


Figure 7: Percentage change of median (non-) software capital, labor and energy use divided by output (base year 2009).

Variable Generation

E	energy use (UoE): electricity consumed - produced electricity + energy sources used for energy generation
L	full-time equivalents (CSS)
P_E	energy costs (CSS) divided by energy use (UoE)
P_L	labour costs (CSS) divided by full-time equivalents (CSS)
VC	variable costs: energy costs & labour costs
S_E	share of energy costs in variable costs
K_{ICT}	ICT capital stock (CoI): calculated with software investments (PIM)
K_N	non-ICT capital stock (CoI): calculated with non-software investments (PIM)
Y	real value added (CSS, deflated)
t	years 2009 - 2016

Perpetual Inventory Method (PIM)

Following Griliches (1980), Harberger (1988) and Hall & Mairesse (1995):
K = capital stock
I = investments

Assuming geometric depreciation at a constant rate δ_t:

$$K_t = (1 - \delta)K_{t-1} + I_1 \tag{11}$$

Assuming K growing at constant investment rate g:

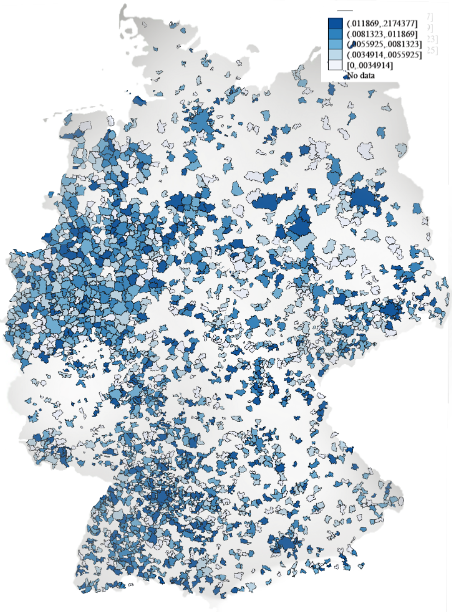
$$g_K = \frac{K_t - K_{t-1}}{K_{t-1}} = \frac{I_t}{K_{t-1}} - \delta \tag{12}$$

$$K_0 = \frac{I_1/r}{g_K + \delta} \tag{13}$$

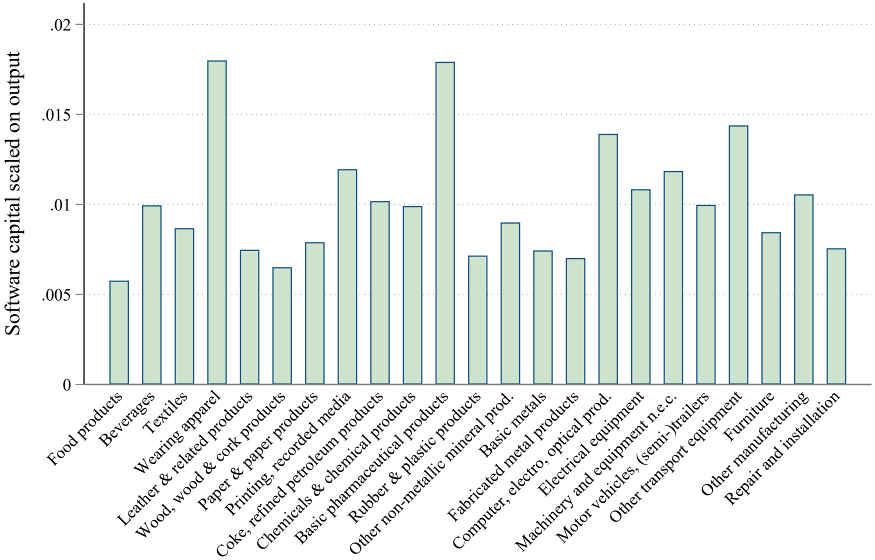
Because investments highly fluctuate over time at the plant or firm level:

$$\hat{I}_1 = \frac{\sum_{t=1}^{3} I_t}{n} \tag{14}$$

Distribution of ICT Capital in Germany



Distribution of ICT Capital within Sectors



Descriptive Statistics

Table 4: Summary statistics.

	Main sample			Energy mix sample		
	mean	median	s.d.	mean	median	s.d.
Relevant variables						
E	33,121,000	2,003,000	404,220,000	25,743,000	2,101,000	384,120,000
L	272	88	1,952	279	92	1,932
P_E (internal)	0.1309	0.1123	0.0940	0.1222	0.1125	0.0584
P_E (external)	0.0915	0.0896	0.0266	0.0883	0.0873	0.0233
P_L	28.69	27.95	9.16	28.78	28.13	9.15
K_{ICT}	257,000	13,00	2,696,000	261,000	14,000	2,557,000
K_N	20,594,000	3,154,000	206,990,000	20,197,000	3,243,000	197,200,000
$\frac{K_{ICT}}{K_N}$	0.0218	0.0035	0.1269	0.0222	0.0038	0.1324
Y	22,791,000	5,026,000	212,600,000	22,925,000	5,219,000	205,470,000
$\frac{Y}{L}$	65,710	57,327	42,814	65,1143	57,367	40,397
$\frac{E}{Y}$	1.0619	0.3815	3.7242	0.9609	0.3816	3.4132
$\frac{K_{ICT}}{Y}$	0.0093	0.0024	0.0637	0.0090	0.0025	0.0293
$\frac{K_N}{Y}$	0.9446	0.5857	4.5565	0.9150	0.5780	4.0443
S_L	0.9098	0.9448	0.1016	0.9133	0.9453	0.0951
S_E	0.0902	0.0552	0.1016	0.0867	0.0547	0.0951
$S_{K_{ICT}}$	0.0041	0.0011	0.0096	0.0041	0.0012	0.0091
S_{K_N}	1.0743	0.6985	1.4423	1.0504	0.6899	1.3994
Only included in the energy mix analysis						
P_{Elec}				0.1378	0.1348	0.0248
P_{NElec}				0.1304	0.0907	0.1192
S_{Elec}				0.0445	0.0287	0.0487
S_{NElec}				0.0422	0.0215	0.0612
Observations	124057			106347		

All monetary variables in €; Energy is measured in kWh. Values have been rounded where necessary to improve clarity.

Source: AFiD; Own calculation

Descriptive Statistics: Energy Prices

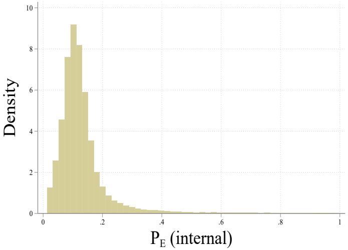


Figure 9: Distribution of internal energy prices.

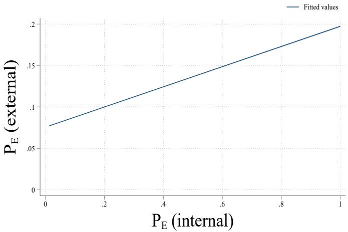


Figure 10: Relationship between internal and external energy prices.

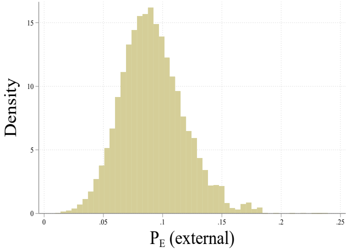


Figure 11: Distribution of external energy prices.

Source: Source: AFiD; Own calculation

Additional Results

Table 5: First-difference estimation results of the total energy model.

	(1) D_{basic}	(2) D_{CS}	(3) D_{all}	(4) No "zero" capital stocks	(5) No early capital stocks	(6) Exogenous prices
$\triangle S_E$						
$\triangle \ln(\frac{P_E}{P_L})$	0.0289***	0.0290***	0.0289***	0.0273***	0.0302***	
	(50.05)	(50.07)	(49.89)	(38.73)	(38.78)	
$\triangle \ln(\frac{P_E}{P_L})$ *ext.*						0.000580
						(1.38)
$\triangle \ln(\frac{K_{ICT}}{Y})$	-0.000247***	-0.000251***	-0.000246***	-0.000429**	-0.000209***	-0.000251***
	(-5.29)	(-5.38)	(-5.33)	(-2.70)	(-4.56)	(-4.82)
$\triangle \ln(\frac{K_N}{Y})$	-0.00107**	-0.00116***	-0.00120***	-0.00156**	-0.00100*	-0.000662
	(-3.09)	(-3.35)	(-3.47)	(-3.20)	(-2.15)	(-1.69)
$\triangle \ln(Y)$	0.00255***	0.00226***	0.00199***	0.00193*	0.00185*	0.00307***
	(4.44)	(3.89)	(3.44)	(2.56)	(2.21)	(4.59)
Year	x	x	x	x	x	x
Economic sector	x	x	x	x	x	x
Multi-unit	x	x	x	x	x	x
Federal state		x	x	x	x	x
Size class		x	x	x	x	x
EEG exemption			x	x	x	x
Producer			x	x	x	x
Observations	90179	90179	90179	63663	59594	90179
Adjusted R^2	0.258	0.260	0.262	0.247	0.286	0.035

t statistics in parentheses. First-difference estimation. Clustered standard errors.* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Additional Results

Table 6: First-difference results of equation 3.

	(1)	(2)
	D_{all}	Exogenous prices
$\triangle ln \frac{E}{Y}$		
$\triangle \ln(\frac{P_E}{P_{PPI}})$	-0.447***	
	(-57.66)	
$\triangle \ln(\frac{P_E}{P_{PPI}})$ *ext.*		-1.181***
		(-47.46)
$\triangle \ln(\frac{K_{ICT}}{K_N})$	-0.00273***	-0.00265***
	(-3.63)	(-3.22)
D_{all}	x	x
Observations	89790	89790
Adjusted R^2	0.226	0.157

t statistics in parentheses. First-difference estimation. Clustered standard errors.* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Additional Results

Table 7: Equation (1) with software capital stocks modified by different depreciation rates.

	(1)	(2)	(3)
		Depreciation rates	
	25 percent	33 percent	50 percent
$\triangle S_E$			
$\triangle \ln(\frac{P_E}{P_L})$	0.0289***	0.0289***	0.0289***
	(49.89)	(49.89)	(49.89)
$\triangle \ln(\frac{K_{ICT}}{Y})$	-0.000297***	-0.000366***	-0.000387***
	(-4.56)	(-4.33)	(-4.08)
$\triangle \ln(\frac{K_N}{Y})$	-0.00121***	-0.00121***	-0.00122***
	(-1.11)	(-1.19)	(-1.16)
$\triangle \ln(Y)$	0.00194***	0.00186**	0.00183**
	(3.33)	(3.18)	(3.12)
D_{all}	x	x	x
Observations	90179	90179	90179
Adjusted R^2	0.262	0.262	0.262

t statistics in parentheses. First-difference estimation. Clustered standard errors.* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Additional Results

Table 8: Equation (1) with software capital stocks modified by different lengths of periods considered for the initial capital stock calculation.

	(1)	(2)
	Number of periods maximal included in initial software capital stocks	
	5	7
$\triangle S_E$		
$\triangle \ln(\frac{P_E}{P_L})$	0.0289***	0.0289***
	(49.89)	(49.89)
$\triangle \ln(\frac{K_{ICT}}{Y})$	-0.000269***	-0.000371***
	(-4.65)	(-4.28)
$\triangle \ln(\frac{K_N}{Y})$	-0.00121***	-0.00122***
	(-3.48)	(-3.50)
$\triangle \ln(Y)$	0.00196***	0.00185**
	(3.38)	(3.16)
D_{all}	x	x
Observations	90179	90179
Adjusted R^2	0.262	0.262

t statistics in parentheses. First-difference estimation. Clustered standard errors.* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.