Energy efficiency in the residential sector

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Pasargad Summer School 2017

Content

- Residential demand for energy is a demand derived from the demand for a warm house, cooked food, hot water, etc.,

- Residential demand for energy can be specified using the basic framework of household production theory.

Household production theory

- According to this theory, households purchase "goods" in the market which serve as inputs that are used in production processes, to produce the “energy services“ which appear as arguments in the household's utility function.

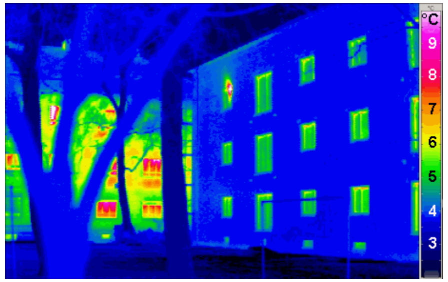
Goods and services

Capital
Energy
Labor

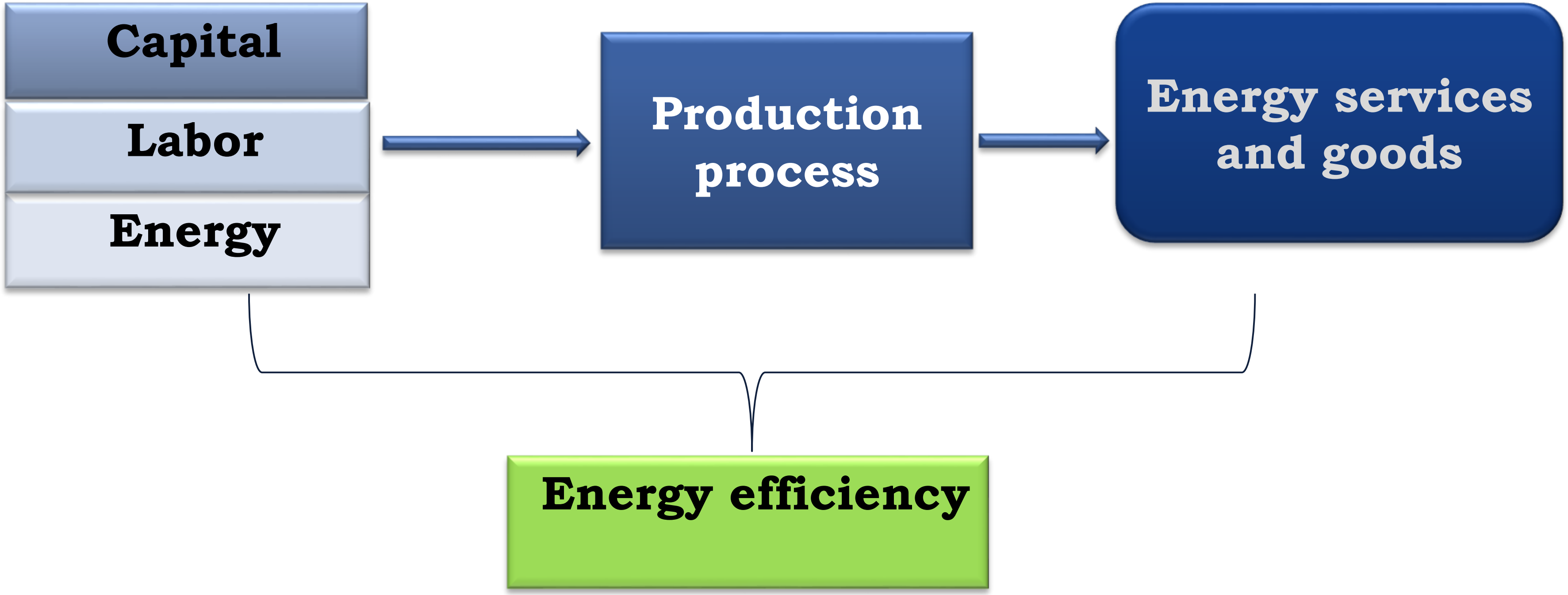
meals, washing,
heating, cooling..
energy services,..

Level of satisfaction

Utility function



Energy efficiency and productive efficiency



Energy services

- The production of energy services implies a choice of

↳ **standard technology** or
↳ **new technology**

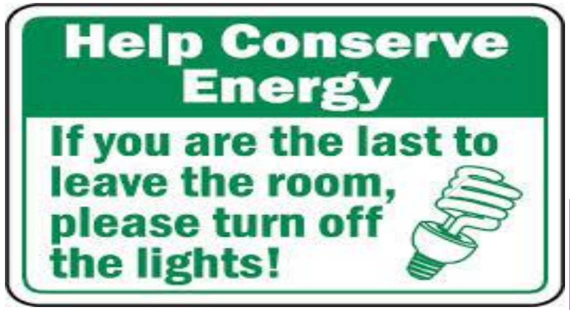
- It implies an investment in durables

- The decision depends on several factors (relative prices, expected prices, discount rate,…behavioural factors, policy measures,..)

Inefficiency in the use of energy (waste of energy) may be due to

- ***low adoption of new energy-efficient technologies*** *(energy efficiency gap)* ***(3)***
- *Use of obsolete technologies*

- ***Inefficient combination of capital and energy (1)***
- ***Inefficient use of electrical appliances / heating system (2)***



Market and behavioral failures

Bounded rationality (low investment literacy)

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Measurement of energy efficiency based on economic foundations

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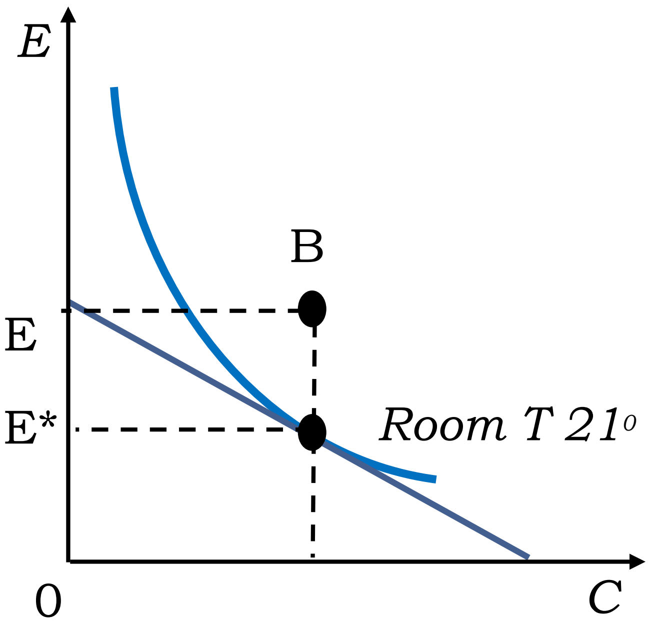
ABSTRACT

Energy efficiency policy is seen as a very important activity by almost all policy makers. In practical energy policy analysis, the typical indicator used as a proxy for energy efficiency is energy intensity. However, this simple indicator is not necessarily an accurate measure given changes in energy intensity are a function of changes in several factors as well as 'true' energy efficiency; hence, it is difficult to make conclusions for energy policy based upon simple energy intensity measures. Related to this, some published academic papers over the last few years have attempted to use empirical methods to measure the efficient use of energy based on the economic theory of production. However, these studies do not generally provide a systematic discussion of the theoretical basis nor the possible parametric empirical approaches that are available for estimating the level of energy efficiency. The objective of this paper, therefore, is to sketch out and explain from an economic perspective the theoretical framework as well as the empirical methods for measuring the level of energy efficiency. Additionally, in the second part of the paper, some of the empirical studies that have attempted to measure energy efficiency using such an economics approach are summarized and discussed.

Inefficiency in the use of energy

Microeconomics approach

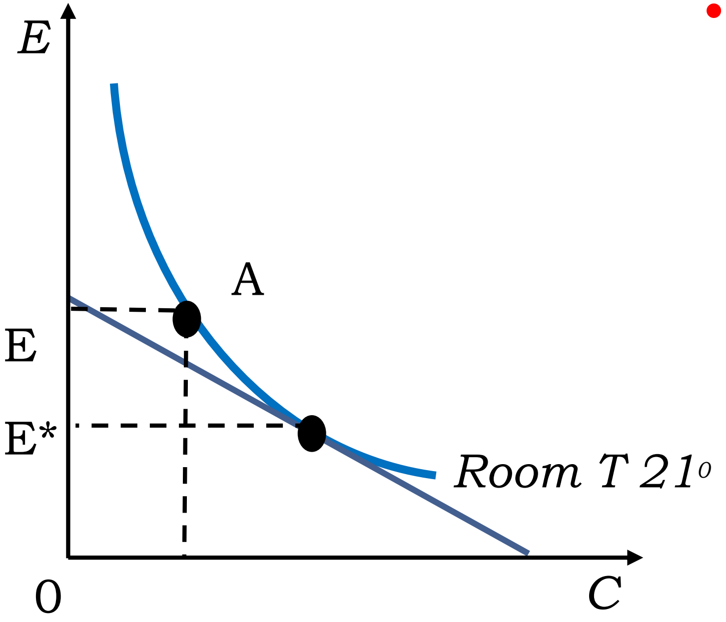


- **Situation 1:** Household ***A*** is using in an inefficient way an appliance or an heating system

Behavior: a household could optimise the amount of time that windows are opened during the day; optimises the use of a cooling/heating system (temperature); turn off the lights,…

Inefficiency in the use of energy

Microeconomics approach

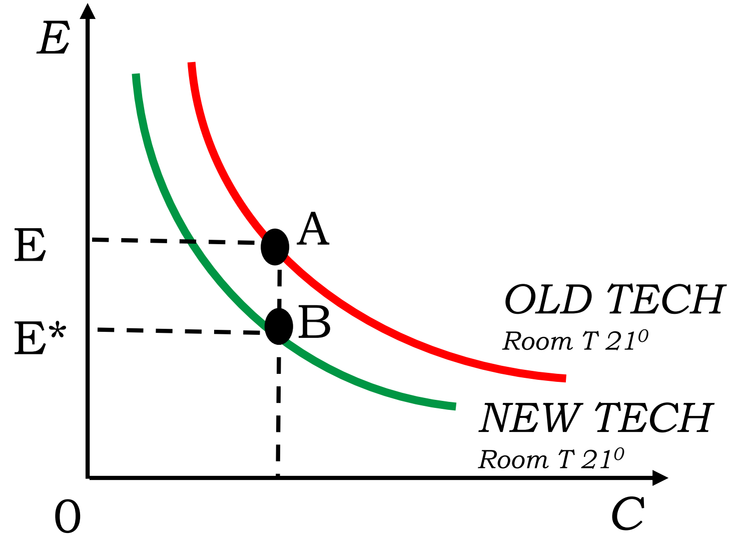


- **Situation 2:** Household ***A*** is using in an inefficient way the inputs (capital and energy)

Substitution of energy with capital:
installing a device on a cooling system to improve the function
of the system; substitution of the windows; insulation of the building

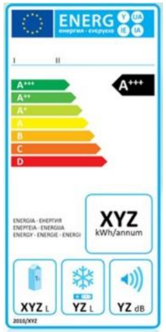
Inefficiency in the use of energy

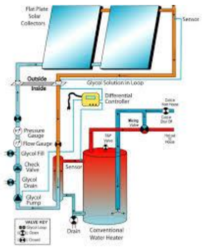
Microeconomics approach



- **Situation 3**: Household is using an old technology ➔ inefficient use of the inputs (capital and/or energy) ➔Energy efficiency gap

Adoption of a new technology: new building technology; more efficient appliances





- ***Example: New technology***:
  Low-energy-consumption building
  - High insulation
  - Continuous renewal of air in the building using an energy-efficient ventilation system
  - Partially Renewable energy sources
  - Design
  - Better comfort (homogeneous distribution of the temperature,indoor air quality,…
- Swiss Label: MINERGIE

Content

A. Definition

B. Measurement

C. Empirical Study

Measurement of energy efficiency

- Possible approaches

  ↳ Partial indicators

  ↳ Bottom up engineering approach

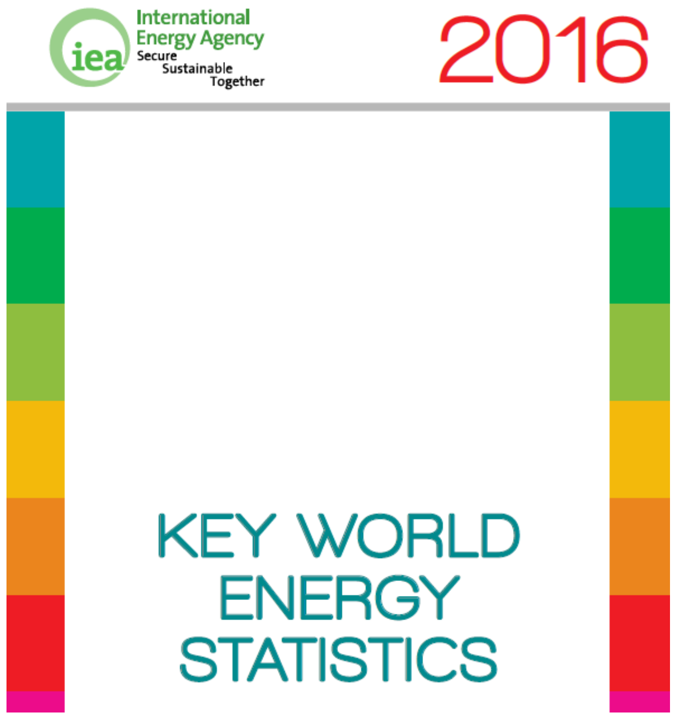
  ↳ **Econometric and linear programming approaches**

Partial indicators

- **Simple ratio of output to energy consumption** (output and inputs measured in physical and or economic units; energy/thermodynamic units,).

↳ **Energy intensity (Energy consumption/GDP; energy consumption per square meter;…)**

↳ **Energy productivity (inverse of energy intensity)**

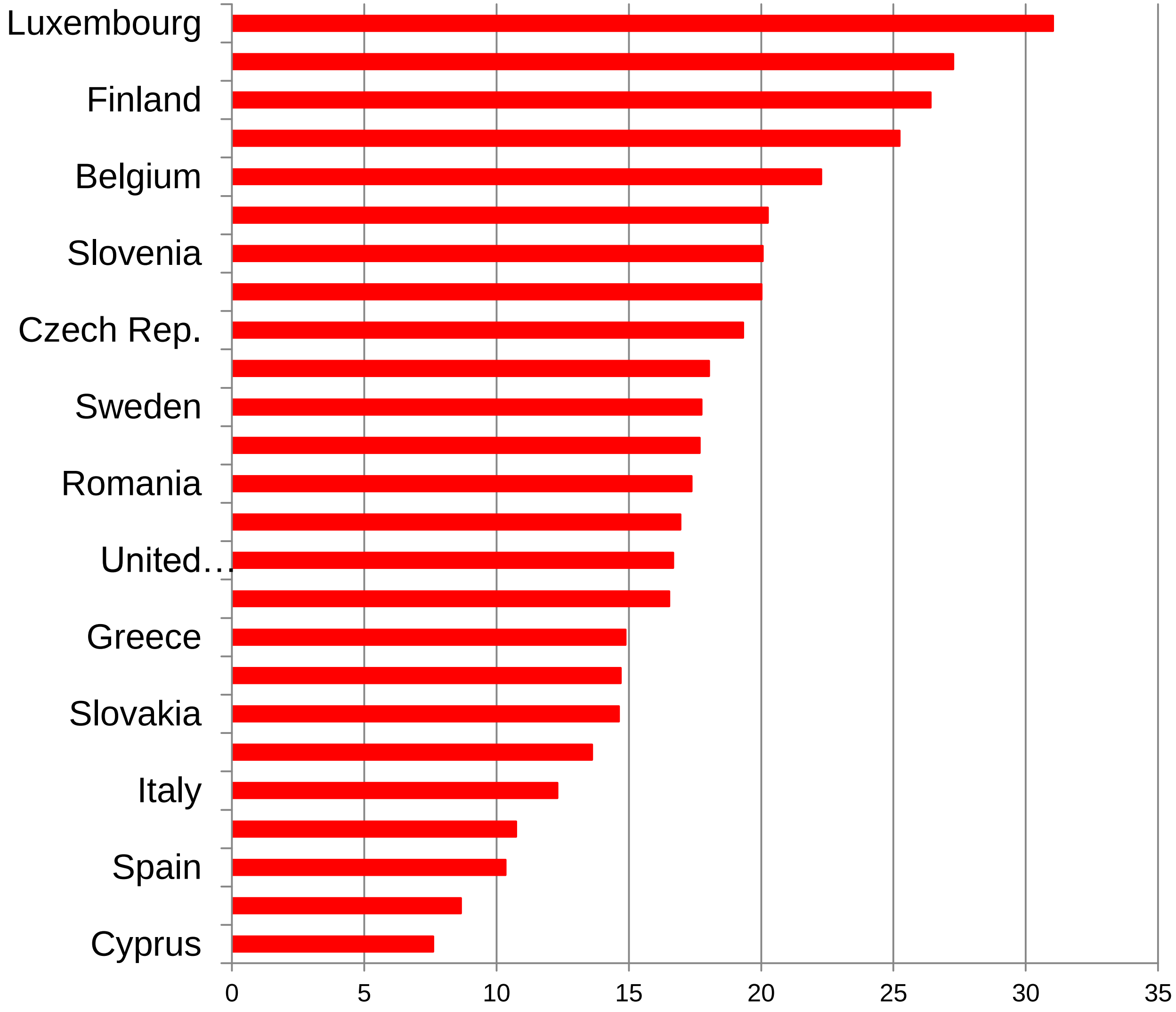


Selected indicators for 2014 (continued)

Energy indicators

TPES/ pop. (toe/capita)	TPES/ GDP (toe/000 2010 USD)	TPES/ GDP (PPP) (toe/000 2010 USD)	Elec. cons./pop. (kWh/ capita)	CO_2/ TPES (t CO_2/ toe)	CO_2/ pop. (t CO_2/ capita)	CO_2/ GDP (kg CO_2/ 2010 USD)	CO_2/ GDP (PPP) (kg CO_2/ 2010 USD)	Region/ Country/ Economy
0.34	0.20	0.09	357	1.45	0.49	0.29	0.13	Ghana
5.94	0.17	0.20	5 818	2.74	16.25	0.47	0.55	Gibraltar
2.12	0.09	0.09	5 047	2.85	6.03	0.27	0.25	Greece
0.83	0.28	0.12	575	1.22	1.01	0.34	0.14	Guatemala
0.39	0.54	0.24	39	0.67	0.26	0.36	0.16	Haiti
0.67	0.30	0.15	697	1.63	1.10	0.48	0.24	Honduras
1.97	0.06	0.04	6 073	3.37	6.62	0.19	0.13	Hong Kong, China
2.31	0.17	0.10	3 966	1.76	4.08	0.29	0.18	Hungary
17.94	0.41	0.44	53 896	0.35	6.25	0.14	0.15	Iceland
0.64	0.38	0.12	805	2.45	1.56	0.92	0.29	India
0.89	0.24	0.09	814	1.94	1.72	0.46	0.17	Indonesia
3.03	0.51	0.19	2 996	2.35	7.12	1.20	0.44	Islamic Rep. of Iran
1.42	0.28	0.10	1 313	2.85	4.05	0.80	0.29	Iraq
2.77	0.05	0.06	5 725	2.65	7.34	0.14	0.16	Ireland
2.76	0.08	0.09	6 604	2.85	7.88	0.24	0.26	Israel
2.41	0.07	0.07	5 002	2.18	5.26	0.16	0.16	Italy

Residential energy consumption (Kwh) per square meters (2011)



Energy intensity in Iran

S. Moshiri / Energy Policy 79 (2015) 177–188

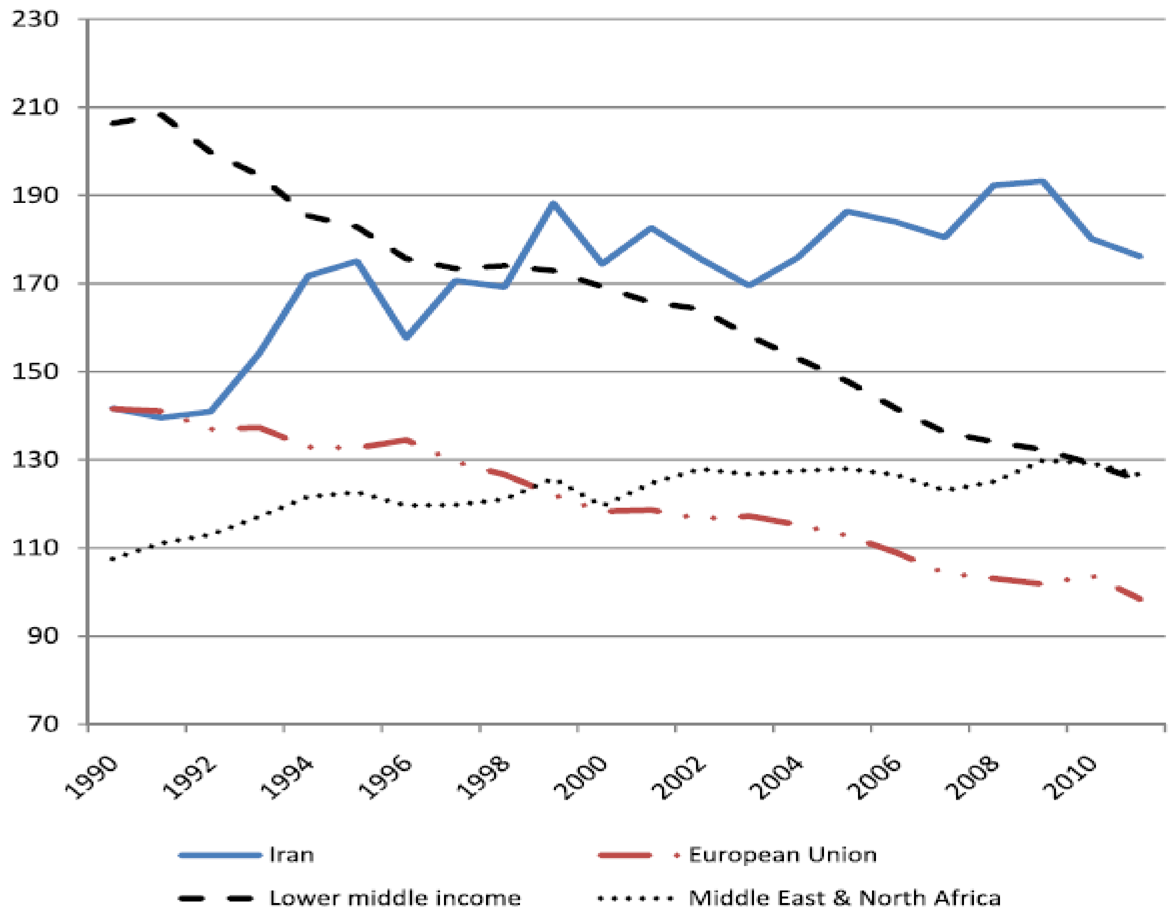
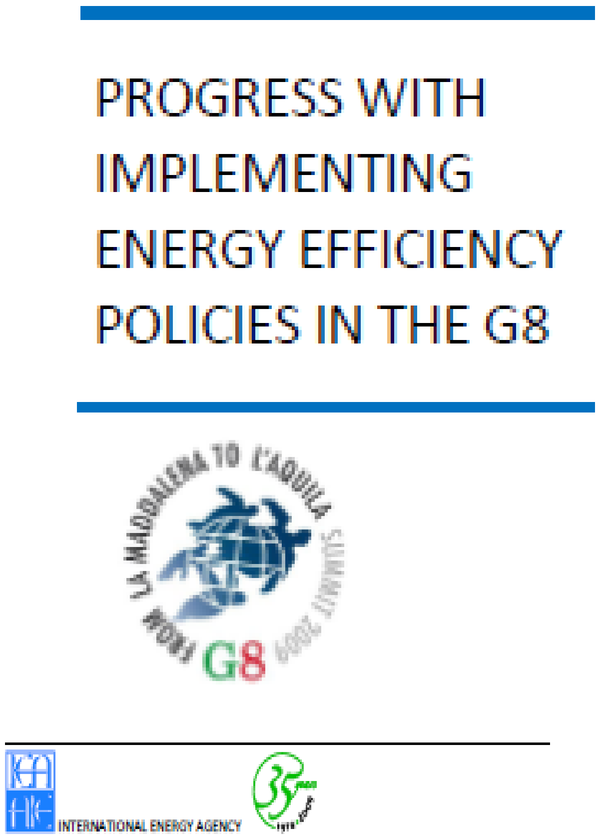


Fig. 1. Energy intensity in Iran and the selected countries. (Energy use in kg of oil equivalent per $1000 constant 2011 PPP GDP).
Source: Word Devlopmet Indicators (2013).

Problems of this indicator



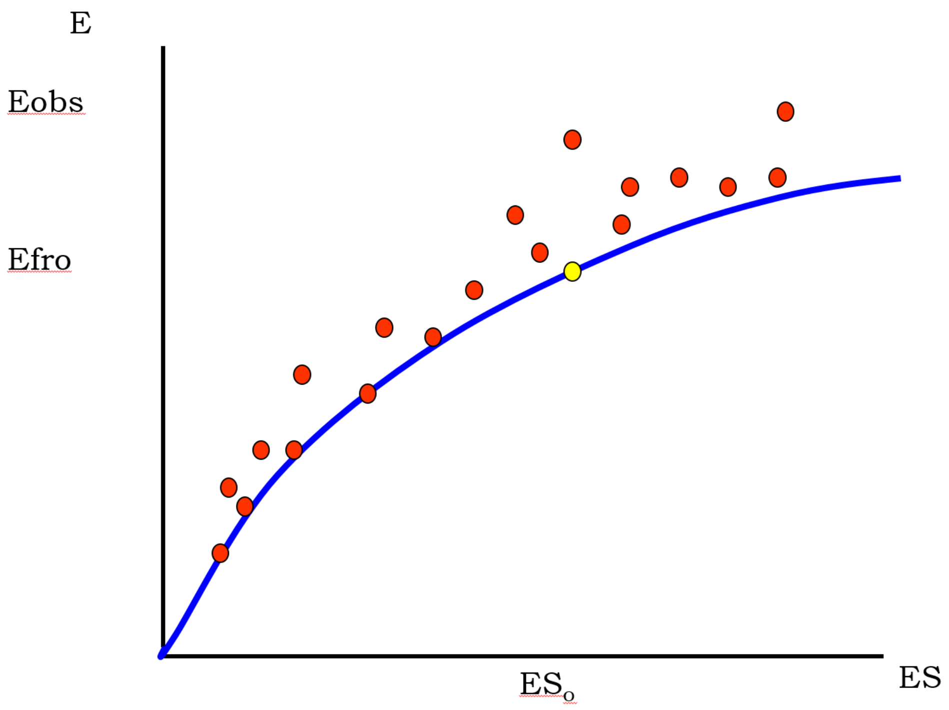
- "Energy intensity is commonly calculated as the ratio of energy use to GDP. Energy intensity is often taken as a proxy for energy efficiency, although this **is not entirely accurate** since changes in **energy intensity are a function of changes in several factors** including the structure of the economy, climate,… and energy efficiency"

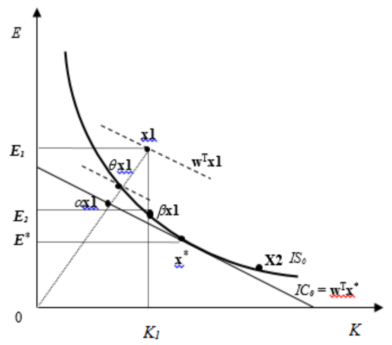
- Energy intensity can vary between countries for several reasons

Econometric and linear programming approaches

- The level of efficiency on the use of energy is based on the estimation of frontier functions.
- A frontier function gives the maximal or minimal level of an economic indicator attainable by an economic agent.

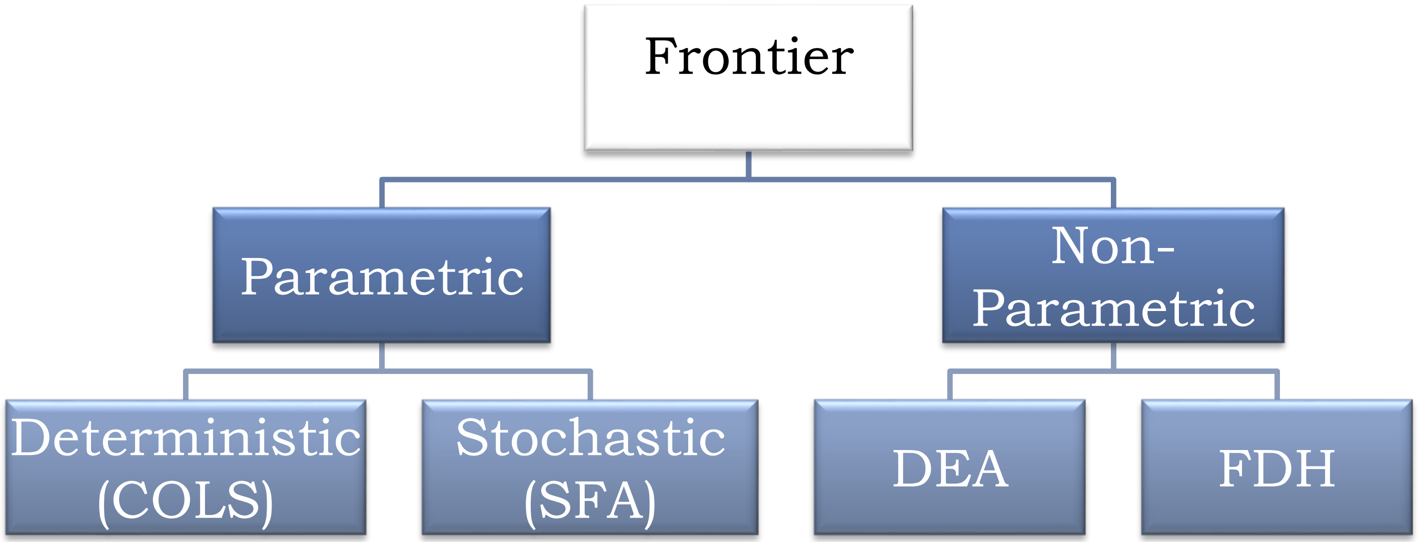
simplified model E=f(energy services, input prices)





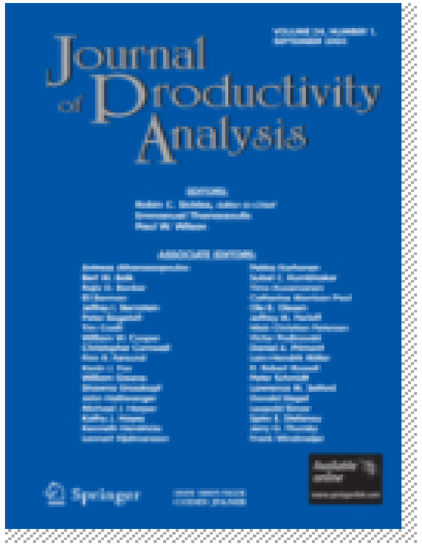
Two approaches

- In the literature we can distinguish two principal types of approaches to measure efficiency
- the *econometric (parametric) approach* and
- the *linear programming (non-parametric)* approach



Two approaches

- Both approaches – ***econometric* and *linear programming*** – have their own advocates. **At least in the scientific community neither one has emerged as dominant**.
- **I will concentrate on the parametric SFA (**Unobserved heterogeneity and panel data)



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Three frontier functions

- The actual empirical studies that estimate the level of efficiency in the use of energy are generally based on the estimation of three frontier functions:

↳ an input requirement function (Boyd, 2008);

↳ a Shephard energy distance function (Zhou et al., 2012);

↳ **An energy demand frontier function (Filippini and Hunt, 2011).**

Residential energy demand model (input demand functionbased on household production theory)

$$x_E = f(p_E, p_C, p_{OG}, Y, ES1, ES2, ..., ..)$$

$$\ln x_E = \alpha_0 + \alpha_{p_E} \ln p_E + \alpha_{p_G} \ln p_G + \alpha_Y \ln Y + \alpha_{ES1} \ln ES1 + \alpha_{ES2} \ln ES2 + ... + \varepsilon$$

usually the amount of energy services is not observed

$$x_E = f(p_E, p_C, p_{OG}, Y, HS, SM, Age, Children, ..., ..)$$

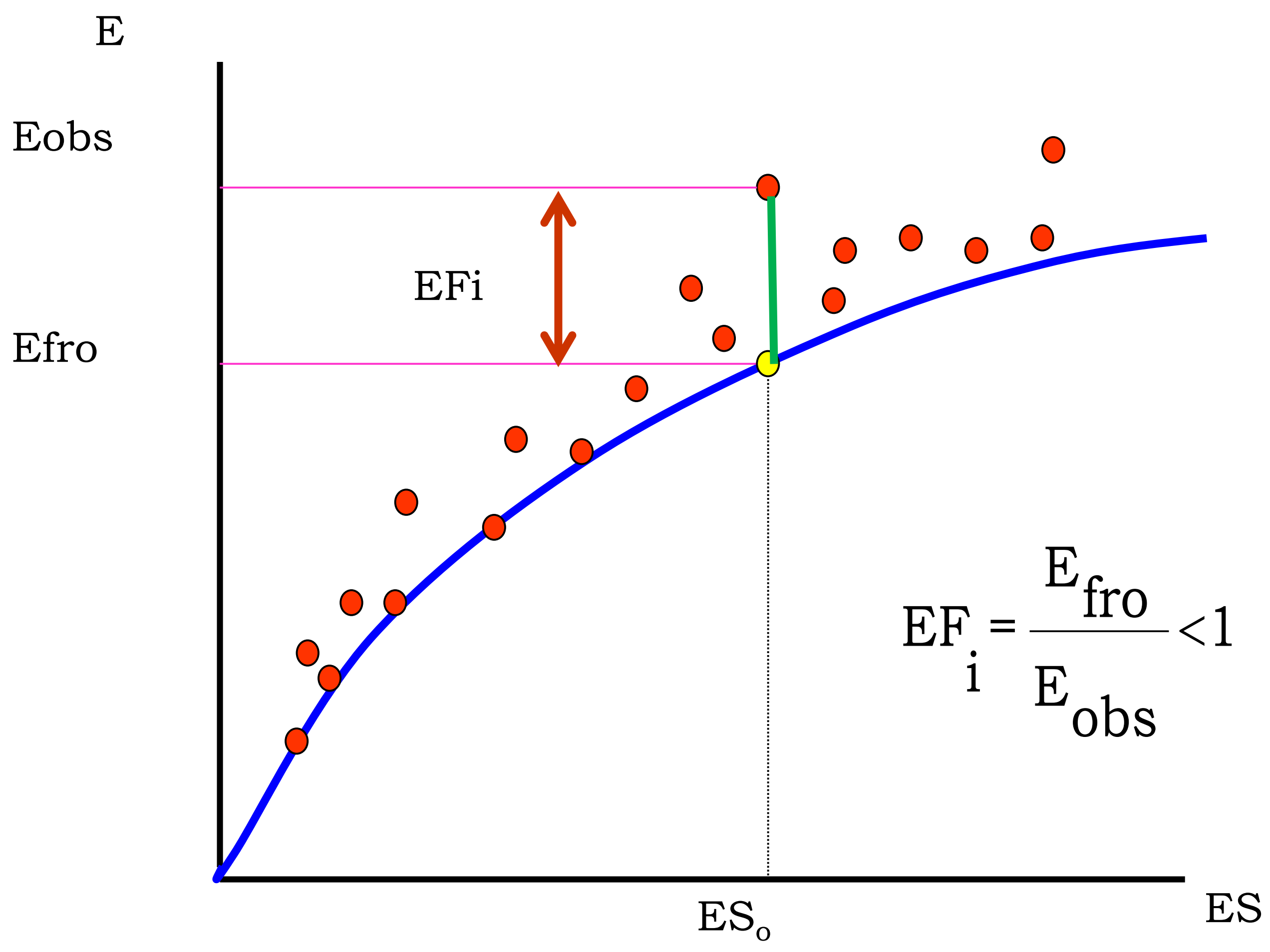
Methodology: an energy demand frontier model

- In the case of an energy demand function **the frontier gives the minimum level of energy necessary for an economy/household/firm to produce any given level of goods and services / energy services**.

- **The distance from the frontier measures the level of energy consumption above the baseline demand**, e.g. the level of energy inefficiency.

An energy demand frontier model

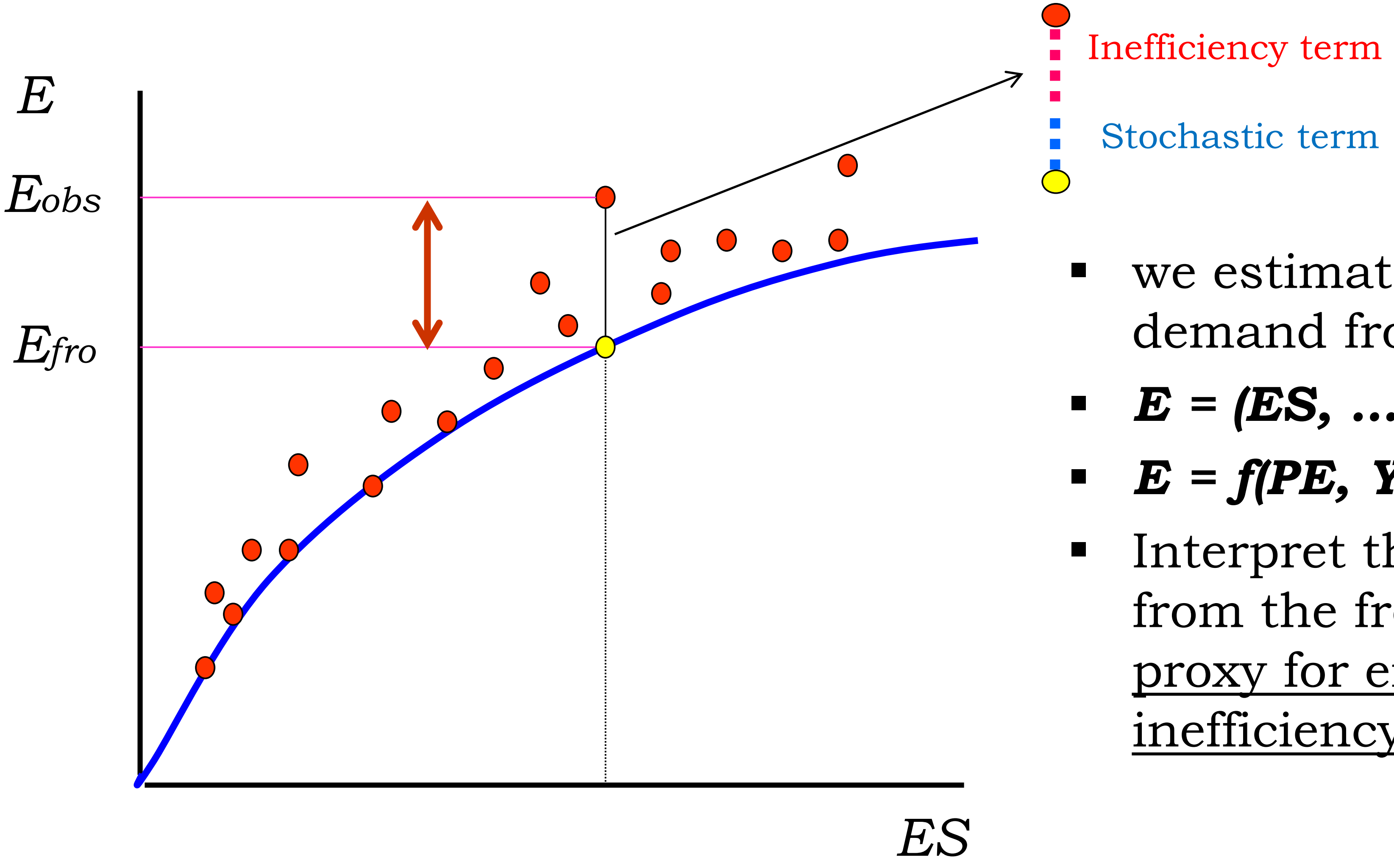
simplified model E=f(energy services, input prices)



Energy efficiency measures the ability of an household to minimize the energy consumption, given a level of energy services

Estimation an energy demand frontier equation

Stocastic frontier energy demand model



- we estimate an energy demand frontier function
- ***E* = *(ES, ….)***
- ***E* = *f(PE, Y, HDD,….)***
- Interpret the distance from the frontier as a <u>proxy for energy inefficiency</u>

Stocastic frontier model using cross-sectional data

$$Ln\ E_i = \alpha + \alpha_y\ lnY_i + \ldots + v_i + u_i \qquad u_i \geq 0$$

a symmetric disturbance capturing the effect of noise and as usual is assumed to be normally distributed

is interpreted as an indicator of energy efficiency and is assumed to be half-normal distributed

$$v_i \sim N[0, \sigma_v^2]$$

$$u_i = |U_i|,\ U_i \sim N[0, \sigma_u^2]$$

Residential energy demand

Data collected trough a survey (cross-section)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	cust_id	city	year	EL	PE	GAS	PG		MILK	PM		HS	SM	INC	dishw	washm	hdd	cdd	.....
2	1	Lugano	2010	1292	20	28000	6.7	.....	40	1.8	.....	1	100	70000	0	1	3602.2	133.3	
3	2	Zurich	2010	17742	18			.....	200	2	.....	5	180	150000	1	0	4000	100	
4	3	Lugano	2010	1912	20	40104.1	6.7	.....	29	1.8	.....	2	90	110000	0	0	3602.2	133.3	
5	4	Bern	2010	2162	16			.....	56	2	.....	2	60	80000	1	0	4100	96	

$$E=f(PE,PG,HS,SM,INC,DISHW,WASHM,DRYER)$$

```
-----------------------------------------------------------------------------
Normal-Half Normal Stoch.Frontier Model
Dependent variable                 LN_E
Log likelihood function      -369.12067
Estimation based on N =    535, K =  10
Inf.Cr.AIC  =    758.2 AIC/N =    1.417
Variances: Sigma-squared(v)=      .21796
           Sigma(v)        =      .46686
           Sigma-squared(u)=      .04059
           Sigma(u)        =      .20147
Sigma = Sqr[(s^2(u)+s^2(v)]=      .50848
Gamma = sigma(u)^2/sigma^2 =      .15699
Var[u]/{Var[u]+Var[v]}     =      .06338
Stochastic Cost Frontier Model, e = v+u
--------+--------------------------------------------------------------------
        |                 Standard            Prob.      95% Confidence
    LN_E|  Coefficient       Error       z     |z|>Z*          Interval
--------+--------------------------------------------------------------------
        |Deterministic Component of Stochastic Frontier Model................
Constant|    12.9747***      .80607    16.10  .0000     11.3948   14.5545
LN_MP_AV|   -1.94048***      .27599    -7.03  .0000    -2.48140  -1.39956
   LN_HS|     .29743***      .05004     5.94  .0000      .19935    .39551
 INC_MID|     .11225*        .05745     1.95  .0507     -.00035    .22486
INC_HIGH|     .25103***      .06554     3.83  .0001      .12258    .37947
   DISHW|     .30953***      .09220     3.36  .0008      .12883    .49024
   WASHM|     .06625         .09342      .71  .4782     -.11685    .24935
   DRYER|     .16935***      .04563     3.71  .0002      .07992    .25878
        |Variance parameters for compound error..............................
   Sigma|     .43154***      .13954     3.09  .0020      .15805    .70502
        |     .50848***      .00076   665.19  .0000      .50698    .50998
--------+--------------------------------------------------------------------
***, **, * ==>  Significance at 1%, 5%, 10% level.
Model was estimated on Sep 08, 2017 at 00:24:09 PM
-----------------------------------------------------------------------------
```

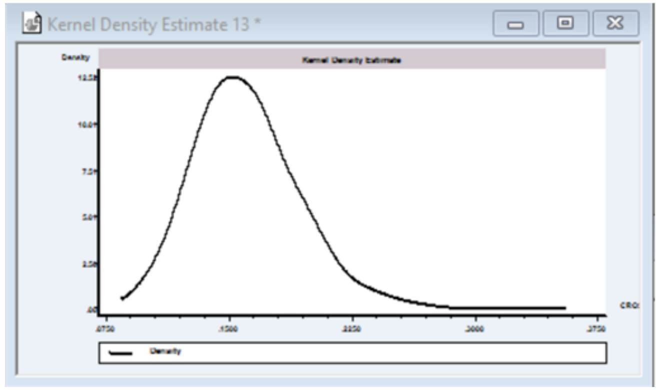
Inefficiency

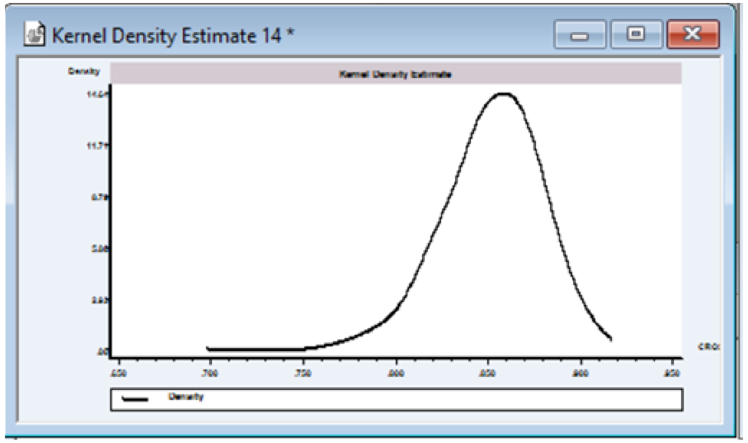
$$E(u_i|\varepsilon_i) = \mu_{*i} + \sigma_* \left[\frac{\phi(-\mu_{*i}/\sigma_*)}{1-\Phi(-\mu_{*i}/\sigma_*)} \right]$$

$$= \sigma_* \left[\frac{\phi(\varepsilon_i \lambda/\sigma)}{1-\Phi(-\varepsilon_i \lambda/\sigma)} + \left(\frac{\varepsilon_i \lambda}{\sigma} \right) \right], \qquad (4.2.12)$$

Descriptive Statistics for 2 variables
DSTAT results are matrix LASTDSTA in curr

Percentiles	CROSS	CROSS1
Sample size	535	535
Min.	.092961	.705713
01th	.100084	.77817
*025	.107907	.791401
05th	.11637	.807851
10th	.125494	.819618
20th	.135072	.831004
25th	.139294	.838189
30th	.143306	.841753
40th	.149287	.847411
Med.	.157465	.854307
60th	.165965	.861355
70th	.172268	.866489
75th	.176512	.869972
80th	.185242	.873725
90th	.198917	.882061
95th	.212678	.889672
*975	.232767	.897238
99th	.247658	.903053
Max.	.348546	.911229





Residential energy demand using panel data
Data collected trough a survey (panel)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	cust_id	city	year	EL	PE	GAS	PG		MILK	PM		HS	SM	INC	dishw	washm	hdd	cdd
2	1	Lugano	2010	1292	20	28000	6.7	.....	40	1.8	.....	1	100	70000	0	1	3602.2	133.3
3	1	Lugano	2011	1481	21	29000	7.4	.....	43	1.8	.....	1	100	70000	0	1	2955.4	115.5
4	1	Lugano	2012	1720	21	27500	7.4	.....	50	1.8	.....	1	100	70000	0	1	3247.8	129.8
5	1	Lugano	2013	1490	21	28500	6.4	.....	41	1.9	.....	1	100	70000	0	1	3436.2	168.1
6	1	Lugano	2014	1492	21	29000	6.4	.....	40	1.9	.....	1	100	70000	0	1	2790.3	73
7	2	Zurich	2010	17742	18			.....	200	2	.....	5	180	150000	1	0	4000	100
8	2	Zurich	2011	19013	18			.....	210	2	.....	5	180	150000	1	0	4032	89
9	2	Zurich	2012	15718	19			.....	202	2	.....	5	180	150000	1	0	4100	88
10	2	Zurich	2013	14544	19			.....	200	2	.....	5	180	150000	1	0	3999	99
11	2	Zurich	2014	11884	20			.....	189	2.1	.....	5	180	150000	1	0	4200	56
12	3	Lugano	2010	1912	20	40104.1	6.7	.....	29	1.8	.....	2	90	110000	0	0	3602.2	133.3
13	3	Lugano	2011	1653	21	36775.1	7.4	.....	21	1.8	.....	2	90	110000	0	0	2955.4	115.5
14	3	Lugano	2012	1806	21	36509.2	7.4	.....	23	1.8	.....	2	90	110000	0	0	3247.8	129.8
15	3	Lugano	2013	1898	21	33149.6	6.4	.....	24	1.9	.....	2	90	110000	0	0	3436.2	168.1
16	3	Lugano	2014	1802	21	35299.9	6.4	.....	23	1.9	.....	2	90	110000	0	0	2790.3	73
17	4	Bern	2010	2162	16			.....	56	2	.....	2	60	80000	1	0	4100	96
18	4	Bern	2011	2304	16			.....	53	2	.....	2	60	80000	1	0	4120	94
19	4	Bern	2012	2243	16			.....	58	2	.....	2	60	80000	1	0	4130	88
20	4	Bern	2013	1948	17			.....	60	2	.....	2	60	80000	1	0	3990	87
21	4	Bern	2014	1965	17			.....	45	2.1	.....	2	60	80000	1	0	4240	52
22	...	...	...	...	...	...	...	.....				...	...	...	...	...	...	...

Advantages of Panel Data

1. Greater number of observations ➔ improves efficiency of the estimation
2. Panel data allow estimation of dynamic relationships even if we only have a small number time periods
3. **Account for heterogeneity of cross-section units: it reduces bias due to**
   – Unobserved heterogeneity/ Omitted variables
4. Panel data (can) vary across time and between individuals ➔ more information reduces problems of multicollinearity

Stochastic Frontier Models SFA
Panel data models

Pooled model

Aigner, Lovell and Schmitt (1977)
Pitt and Lee (1981)

FE and RE Models

<u>Original</u>

Pitt and Lee (1981)

Schmidt and Sickles (1984)

Battese and Coelli (1986)

True random and true fixed effects

<u>Original</u>

Greene (2005)

<u>With Mundlak correction</u>

Farsi,Filippini and Kuenzle (2005)

Farsi, Filippini, Greene (2005)

Latent class models

Kumbhakar, Orea (2005)

Generalized true random and true fixed effects

<u>Transient and persistent part</u>

Colombi et. Al. (2014)

Filippini/ Greene (2015)

Pooled model

$$\ln E_{it} = \alpha + \boldsymbol{\beta}'\mathbf{x}_i + v_{it} + u_{it}$$

$$v_{it} \sim N[0, \sigma_v^2]$$

$$u_{it} = |U_{it}| \text{ and } U_{it} \sim N^+[0, \sigma_u^2]$$

v_{it} and u_{it} are distributed independently of each other, and of the regressors

A symmetric disturbance capturing the effect of noise and as usual is assumed to be normally distributed

It is interpreted as an indicator of energy efficiency and is assumed to be half-normal distributed
Time varying inefficiency

RE model (PITT and LEE)

$$\ln E_{it} = \alpha + \boldsymbol{\beta}'\mathbf{x}_i + v_{it} + u_i$$

$$v_{it} \sim N[0, \sigma_v^2]$$

$$u_i \sim N^+[0, \sigma_u^2]$$

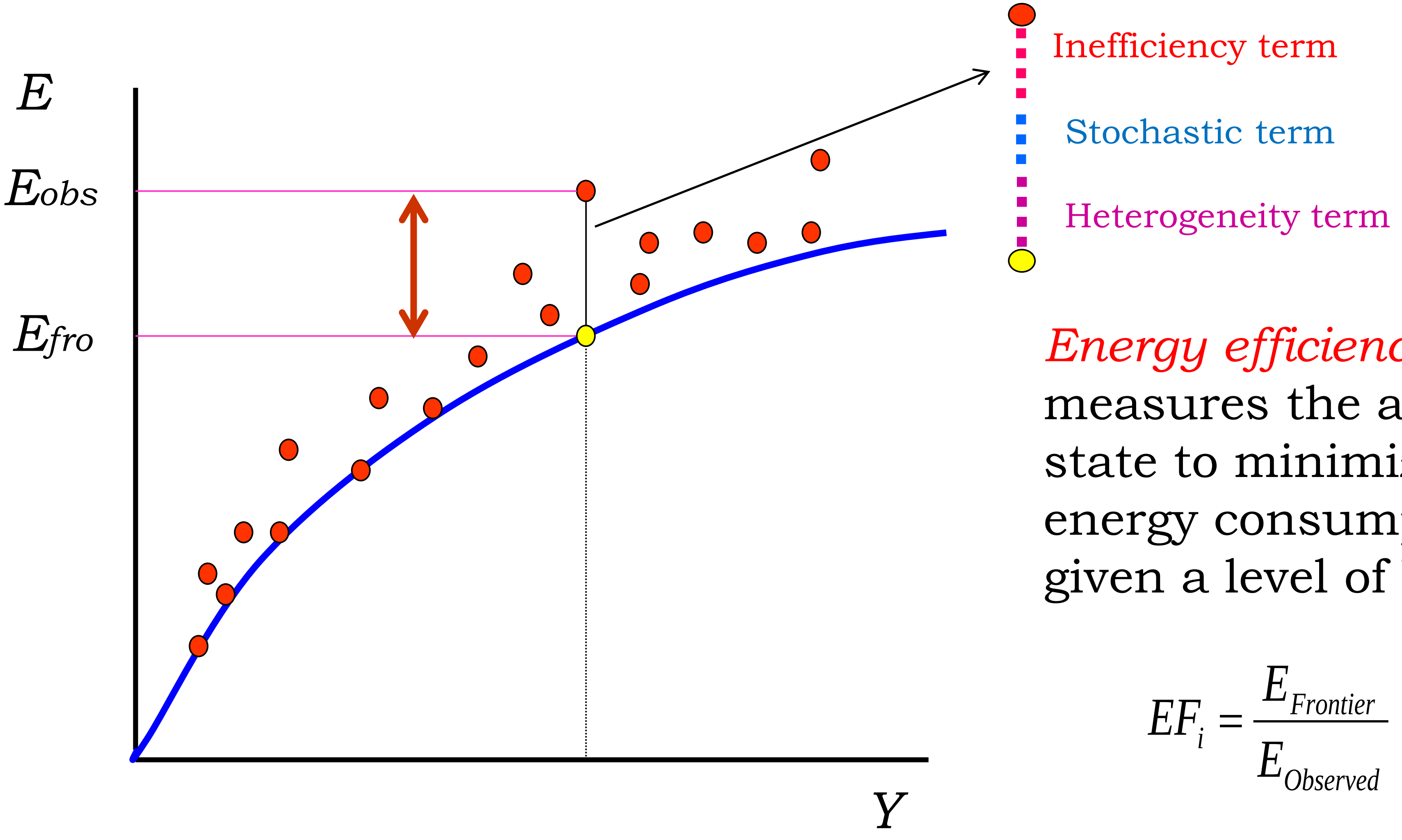
v_{it} and u_i are distributed independently of each other, and of the regressors

A symmetric disturbance capturing the effect of noise and as usual is assumed to be normally distributed

It is interpreted as an indicator of energy efficiency and is assumed to be half-normal distributed
Time invariant inefficiency

True random effects model (TRE)

Greene (2005)



Energy efficiency:
measures the ability of a state to minimize the energy consumption, given a level of Y

$$EF_i = \frac{E_{Frontier}}{E_{Observed}} \leq 1$$

TRE model

$$\ln E_{it} = w_i + \boldsymbol{\beta}'\mathbf{x}_{it} + v_{it} + u_{it}$$

Unobserved time invariant heterogeneity

A symmetric disturbance capturing the effect of noise and as usual is assumed to be normally distributed

It is interpreted as an indicator of energy efficiency and is assumed to be half-normal distributed

Time varying inefficiency

$$v_{it} \sim N[0, \sigma_v^2]$$

$$u_{it} \sim N^+[0, \sigma_u^2]$$

$$w_i \sim \mathrm{N}\ (0, s_w^{\ 2})$$

w_i, v_{it} and u_{it} are distributed independently of each other, and of the regressors

Maximum Simulated Likelihood (RPM)

GTRE model (persistent/transient)

Filippini and Greene (2015)

$$\ln E_{it} = w_i + h_i + \boldsymbol{\beta}'\mathbf{x}_{it} + v_{it} + u_{it}$$

$v_{it} \sim N[0, \sigma_v^2]$

$u_{it} \sim N^+[0, \sigma_u^2]$

$w_i \sim \mathrm{N}\ (0, s_w{}^2)$

$h_i \sim \mathrm{N}^+(0, s_h{}^2)$

w_i, h_i, v_{it} and u_{it} are distributed independently of each other, and of the regressors

Maximum Simulated Likelihood (RPM)

Unobserved time invariant heterogeneity

A symmetric disturbance capturing the effect of noise and as usual is assumed to be normally distributed

Time transient inefficiency

Time persistent inefficiency

Random Coefficients Frontier Model
Dependent variable LN_E
Log likelihood function -107.93895
Estimation based on N = 2605, K = 12
Inf.Cr.AIC = 239.9 AIC/N = .092
Unbalanced panel has 545 individuals
Simulation based on 150 Halton draws

Closed Skew Normal(LR/SR)Frontier Model

---- Short and Long Run Components ----
-------- Short Run Time Varying ---------
Sigma(uit) (1 sided) = .16812
Sigma(vit) (symmetric) = .14154
---------- Long Run Time Fixed ----------
Theta(ai) (1 sided) = 1.11916
Theta(fi) (symmetric) = .51262

LN_E	Coefficient	Standard Error	z	Prob. |z|>Z*	95% Confidence Interval	
	Production / Cost parameters, nonrandom first					
LN_MP_AV	-.28756***	.03100	-9.27	.0000	-.34833	-.22679
LN_HS	.26727***	.00751	35.59	.0000	.25255	.28199
INC_MID	.03143***	.00947	3.32	.0009	.01287	.04999
INC_HIGH	.09749***	.01055	9.24	.0000	.07682	.11816
DISHW	.12175***	.01484	8.20	.0000	.09266	.15085
WASHM	.06149***	.01540	3.99	.0001	.03130	.09168
DRYER	.07148***	.00741	9.65	.0000	.05696	.08600
	Means for random parameters					
Constant	8.47152***	.09075	93.35	.0000	8.29365	8.64939
	Theta_fi = std. dev. of time fixed symmetric f(i)					
Constant	.51262***	.00358	143.29	.0000	.50561	.51963
	Variance parameters for v +/- u					
Sigma	.21977***	.00290	75.76	.0000	.21408	.22545
	Asymmetry parameter, lambda					
Lambda	1.18782***	.05382	22.07	.0000	1.08234	1.29331
	Theta_ai = std. dev. of time fixed one sided a(i)					
Theta_ai	1.11916***	.02896	38.64	.0000	1.06239	1.17593

***, **, * ==> Significance at 1%, 5%, 10% level.
Model was estimated on Sep 08, 2017 at 01:11:25 PM

Variable	Mean	Standard Deviation	Minimum	Maximum	Cases	Missing Values
EFF_SR	.882172	.04346	.34792	.971789	2605	0
EFF_LR	.712525	.004043	.682139	.780171	2605	0

Descriptive Statistics for 2 variables
DSTAT results are matrix LASTDSTA in current project.

Percentiles	EFF_SR	EFF_LR
Sample size	2605	2605
Min.	.34792	.682139
01th	.710866	.701591
*025	.775615	.706042
05th	.805159	.707394
10th	.838734	.709066
20th	.862661	.710846
25th	.869627	.711186
30th	.87508	.711616
40th	.884157	.712119
Med.	.890675	.712618
60th	.896025	.713153
70th	.902164	.713686
75th	.905244	.71407
80th	.908958	.714457
90th	.918813	.715527
95th	.929705	.716895
*975	.940688	.71754
99th	.95166	.721209
Max.	.971789	.780171

Content

A. Definition

B. Measurement

C. Empirical Study

ETH zürich

The role of energy and investment literacy for residential electricity demand and end-use efficiency

Blasch J. Boogen N., Filippini M., Kumar N., (forthcoming). The role of energy and investment literacy for residential electricity demand and end-use efficiency. ***Energy Economics***

Research questions

- Measure the level of efficiency in the use of energy (electricity)

- Identifying what drives the differences in the level of *En.Eff.* between Swiss households

↳ role of **behavioral factors**
↳ role of **investment literacy**
↳ role of **energy literacy**

Literacy

- **Energy related investment literacy (financial literacy)**

- Investment literacy can be defined as the ability to perform an investment analysis and to calculate the lifetime cost of an appliance or energy-efficient renovation.

- **Energy literacy**

- Energy literacy can be defined as household's knowledge about energy production and consumption

Electricity demand model

$$\ln E_{it} = \alpha_0 + \alpha_p \ln p^E_{it} + \alpha_M M_{it} + \alpha_H H_{it} + \alpha_{ES} ES_{it} + \alpha_L LOC_{it} + \alpha_w W_{it} + \alpha_{LT} LIT_{it} + \alpha_{BE} BEH_{it} + \alpha_T T_t + \alpha_{TT} T^2_t + \varepsilon_{it} \quad (1)$$

where E_{it} is the electricity demand (in kWh), p^E_{it} is the electricity price, M_{it} is a vector of household characteristics, H_{it} is a vector of dwelling characteristics, ES_{it} is the amount of energy services consumed, LOC_{it} is the utility service area and W_{it} is the number of heating degree days (HDD) and cooling degree days (CDD) that the household experiences. LIT_{it} represents the level of energy and investment literacy of the respondent, BEH_{it} captures the energy saving behaviour of the household, T_t and T^2_t capture the time trend, and ε_{it} is the overall error term. This equation represents the minimum electricity consumption as a function of electricity price, weather influences, household and dwelling characteristics, stock of special appliances[8], level of energy services, energy and investment literacy, and energy saving behaviour. We use a log-log model specification in the empirical analysis presented in this paper.

The GTREM specification

Model: $y_{it} = \alpha + \beta' \mathbf{x}_{it} + \varepsilon_{it}$

Full random error (ε_{it}):

$$\begin{cases} \varepsilon_{it} = w_i + h_i + u_{it} + \nu_{it} \\ u_{it} \sim N^+[0, \sigma_u^2] \\ h_i \sim N^+[0, \sigma_h^2] \\ \nu_{it} \sim N[0, \sigma_\nu^2] \\ w_i \sim N[0, \sigma_w^2] \end{cases}$$

Note: A log-log model specification is used in the empirical analysis. $E(h_i|\mathbf{y}_i)$ captures the persistent inefficiency and $E(u_{it}|\mathbf{y}_i)$ captures the transient inefficiency.

Energy Literacy and Energy Saving Behaviour

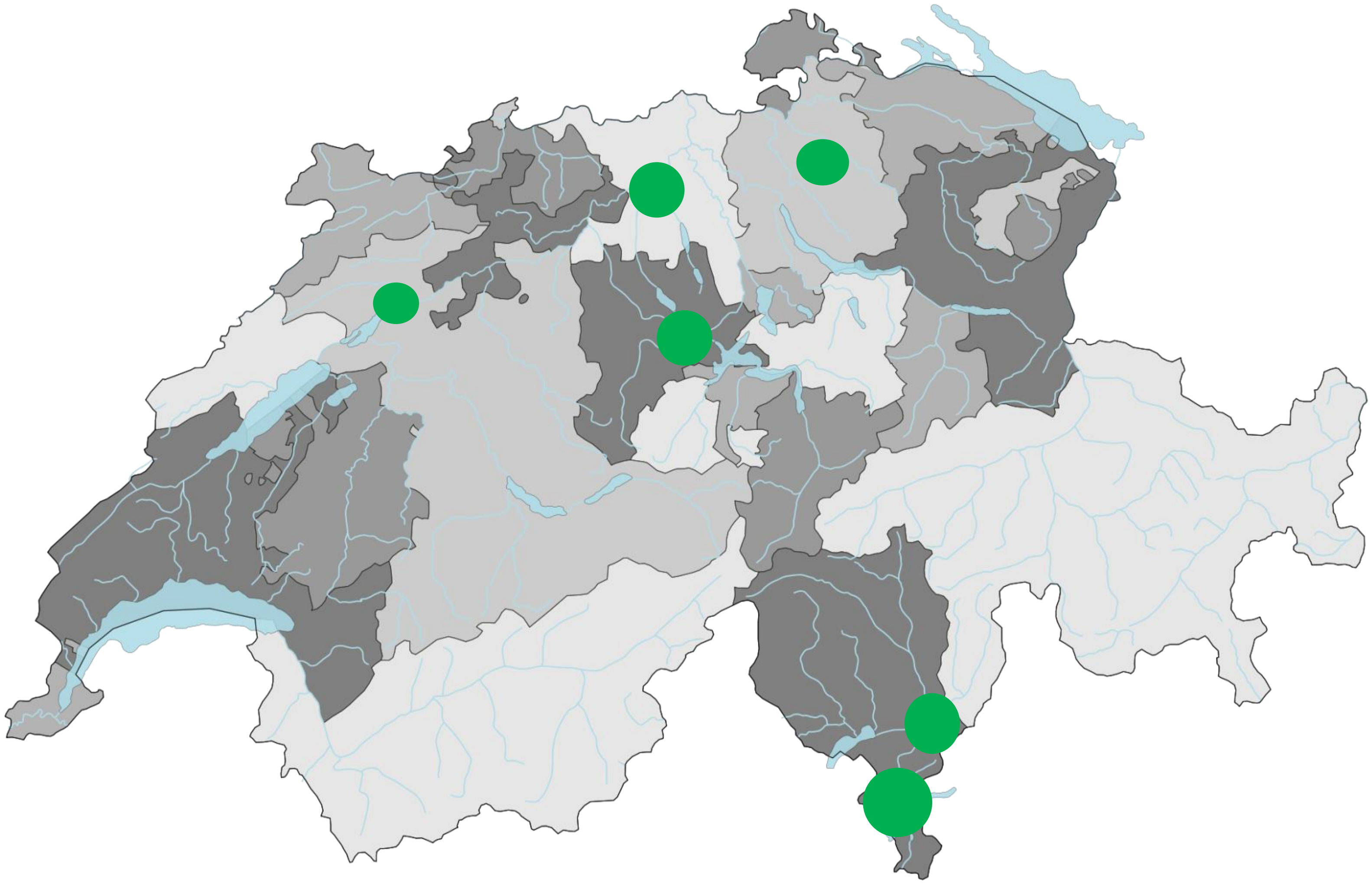
- **Energy literacy index (0 –14)**
  - ↳ average price of 1 kWh
  - ↳ usage cost of household appliances (2 Qs)
  - ↳ Consumption of household appliances (3 Qs)
  - ↳ compound interest calculation

- **Energy saving behaviour index (0-4)**
  - ↳ running washing machine only on full load
  - ↳ washing clothes on a lower water temperature
  - ↳ dishwasher cycle based on level of dirtiness
  - ↳ switching off appliances

- **Investment literacy index**
  - ↳ Compound interest question
  - ↳ …

Data

Household Survey on Energy Usage



- 6 Swiss Electric and Gas utilities
- Survey organization
  - Online survey in 2015 - 2016
  - Randomly chosen sample
  - Consumption data: 2010 - 2014
- Dataset used here:
  - 6 utilities: Aarau, Winterthur Biel, Luzern, Lugano and Bellinzona
  - ~1994 households

Questionnaire

- House/apartment characteristics
- Socio-demographics
- Appliance stock and energy services
- Attitudes towards environment
- Energy-related behaviour
- Energy related knowledge (energy-literacy)

- *Representativeness*:
  → gender, age and income groups are sufficiently covered
- Share of respondents who donated money to an environmental organization in line with Swiss average → limited self-selection of pro-environmental households

Estimation results

(Log) price of electricity	-0.3032***	(0.037)	-0.2882***	(0.037)
Single family household	0.1674***	(0.007)	0.2305***	(0.007)
(Log) household size	0.3472***	(0.011)	0.4338***	(0.011)
(Log) dwelling size in m2	0.3921***	(0.009)	0.4778***	(0.009)

(Log) energy literacy index	-0.0126***	(0.004)	-0.0157***	(0.004)
Investment literacy	-0.1137***	(0.006)	-0.1109***	(0.006)
Time trend (linear)	-0.1190***	(0.022)	-0.1072***	(0.022)

	GTREM-1		GTREM-2	
	Coefficient	*Std. error*	*Coefficient*	*Std. error*
(Log) price of electricity	-0.3032***	(0.037)	-0.2882***	(0.037)
Single family household	0.1674***	(0.007)	0.2305***	(0.007)
(Log) household size	0.3472***	(0.011)	0.4338***	(0.011)
(Log) dwelling size in m2	0.3921***	(0.009)	0.4778***	(0.009)
Has young people	-0.0449***	(0.008)	0.0011	(0.008)
Has elderly people	0.0346***	(0.006)	0.0215***	(0.006)
Income in 6k - 12k	-0.0119**	(0.006)	-0.0090	(0.006)
Income above 12k	-0.0180**	(0.009)	-0.0134	(0.009)
Built in 1940 - 1970	-0.0773***	(0.008)	-0.0736***	(0.008)
Built in 1970 - 2000	0.0440***	(0.007)	0.1076***	(0.007)
Built in 2000 - 2015	-0.0558***	(0.009)	0.0408***	(0.009)
Minergie house	0.0185*	(0.010)	0.0633***	(0.010)
Absent 5 to 8 weeks/year	-0.1506***	(0.009)	-0.1526***	(0.009)
Has 2nd fridge	0.1042***	(0.007)	0.1494***	(0.007)
Has separate freezer	0.1126***	(0.005)	0.1481***	(0.005)
No special appliances	-0.0767***	(0.006)	-0.0858***	(0.006)
(Log) number of cooked meals	0.0021	(0.006)	—	—
(Log) dishwashing cycles	0.1151***	(0.004)	—	—
(Log) cloth washing/drying cycles	0.1009***	(0.004)	—	—
(Log) hours of tv/pc	0.1708***	(0.004)	—	—
Cooks using electricity	0.0957***	(0.008)	0.1598***	(0.008)
(Log) heating degree days	-0.1051	(0.111)	-0.0777	(0.110)
(Log) cooling degree days	0.1923***	(0.046)	0.1717***	(0.046)
Region = Aarau	0.0559***	(0.020)	0.0314	(0.020)
Region = Winterthur	-0.1312***	(0.040)	-0.0879**	(0.040)
Region = Biel/Bienne	0.0768***	(0.024)	0.0396	(0.024)
Region = Lucerne	-0.0514***	(0.017)	-0.0846***	(0.017)
Region = Bellinzona	-0.2524***	(0.066)	-0.2864***	(0.065)
University degree	-0.0144***	(0.006)	-0.0434***	(0.006)
University degree (partner)	-0.0185***	(0.007)	-0.0088	(0.007)
(Log) energy saving behaviour	-0.0227***	(0.007)	-0.0412***	(0.007)
(Log) energy literacy index	-0.0126***	(0.004)	-0.0157***	(0.004)
Investment literacy	-0.1137***	(0.006)	-0.1109***	(0.006)
Time trend (linear)	-0.1190***	(0.022)	-0.1072***	(0.022)
Time trend (quadratic)	0.0230***	(0.004)	0.0213***	(0.004)
α	5.6722***	(0.719)	5.5717***	(0.713)
σ_w	0.3960***	(0.002)	0.4228***	(0.002)
$\sigma_{(\nu+u)}$	0.2542***	(0.003)	0.2894***	(0.003)
λ	0.7553***	(0.041)	1.2193***	(0.041)
σ_h	0.5411***	(0.017)	0.2696***	(0.014)
Observations:	8295		8295	
Log-likelihood:	-1735.7		-1867.4	

***, **, * $\Rightarrow$ Significance at 1%, 5%, 10% level.

Different econometric specifications!

Estimation results

Table 5: Efficiency scores (transient and persistent).

Efficiency type	*Median*	*Mean*	*Std. Dev.*	*Minimum*	*Maximum*
GTREM-1 (with energy services)					
Transient	0.894	0.892	0.026	0.634	0.974
Persistent	0.785	0.784	0.013	0.394	0.841
GTREM-2 (without energy services)					
Transient	0.856	0.848	0.051	0.395	0.966
Persistent	0.841	0.840	0.006	0.675	0.951

Conclusions

- Estimation of an indicator of the level of energy efficiency for each household
  → Measure of efficiencies (median values)
  ➪ **Persistent efficiency**: **78 %**
  ➪ **Transient efficiency**: **89 %**

- **Higher persistent inefficiency**
  ➪ structural problems faced by household
  ➪ systematic behavioural shortcomings

- **Positive role of energy related literacy and energy saving behaviour**
  ➪ Electricity consumption is lower in households exhibiting energy saving behaviours
  ➪ Higher level of energy literacy is associated with lower electricity consumption
  ➪ Higher level of financial literacy is associated with lower electricity consumption

Policy implication
Information
Public campaign
Educational program

References

- Blasch J. Boogen N., Filippini M., Kumar N., (forthcoming). The role of energy and investment literacy for residential electricity demand and end-use efficiency. ***Energy Economics***.

- Filippini M., Hunt L., (2016). Measuring Persistent and Transient Energy Efficiency in the US, ***Energy Efficiency***, 9(3), 663-675.

- Filippini M., Greene W., (2016). Persistent and Transient Productive Inefficiency: A Maximum Simulated Likelihood Approach. ***Journal of Productivity Analysis***, 45(2), 187-196.

Appendix

$$\varepsilon_i = v_i + u_i$$

$$f(v) = \frac{1}{\sqrt{2\pi}\sigma_v} \cdot \exp\left\{-\frac{v^2}{2\sigma_v^2}\right\}.$$

$$f(u) = \frac{2}{\sqrt{2\pi}\sigma_u} \cdot \exp\left\{-\frac{u^2}{2\sigma_u^2}\right\},$$

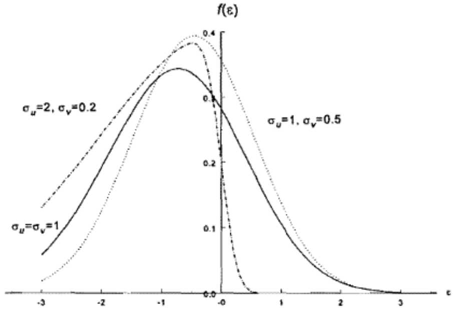


Figure 3.3 Normal–Half Normal Distributions

Joint density
(product of the individual density functions)

Marginal density

$$f(\varepsilon) = \int_0^\infty f(u,\varepsilon)\,du$$
$$= \int_0^\infty \frac{2}{2\pi\sigma_u\sigma_v} \cdot \exp\left\{\frac{-u^2}{2\sigma_u^2} - \frac{(\varepsilon-u)^2}{2\sigma_v^2}\right\} du$$
$$= \frac{2}{\sqrt{2\pi}\sigma} \cdot \left[1 - \Phi\left(\frac{-\varepsilon\lambda}{\sigma}\right)\right] \cdot \exp\left\{-\frac{\varepsilon^2}{2\sigma^2}\right\}$$
$$= \frac{2}{\sigma} \cdot \phi\left(\frac{\varepsilon}{\sigma}\right) \cdot \Phi\left(\frac{\varepsilon\lambda}{\sigma}\right),$$

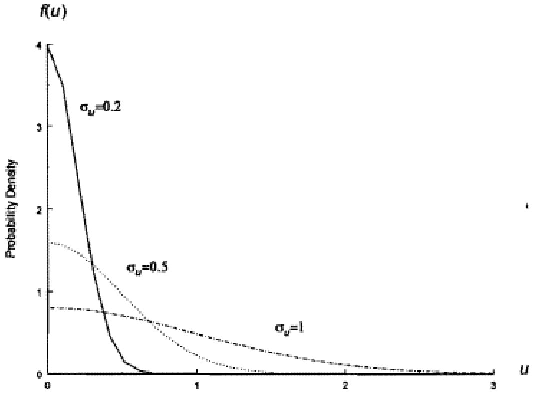


Figure 3.2 Half Normal Distributions

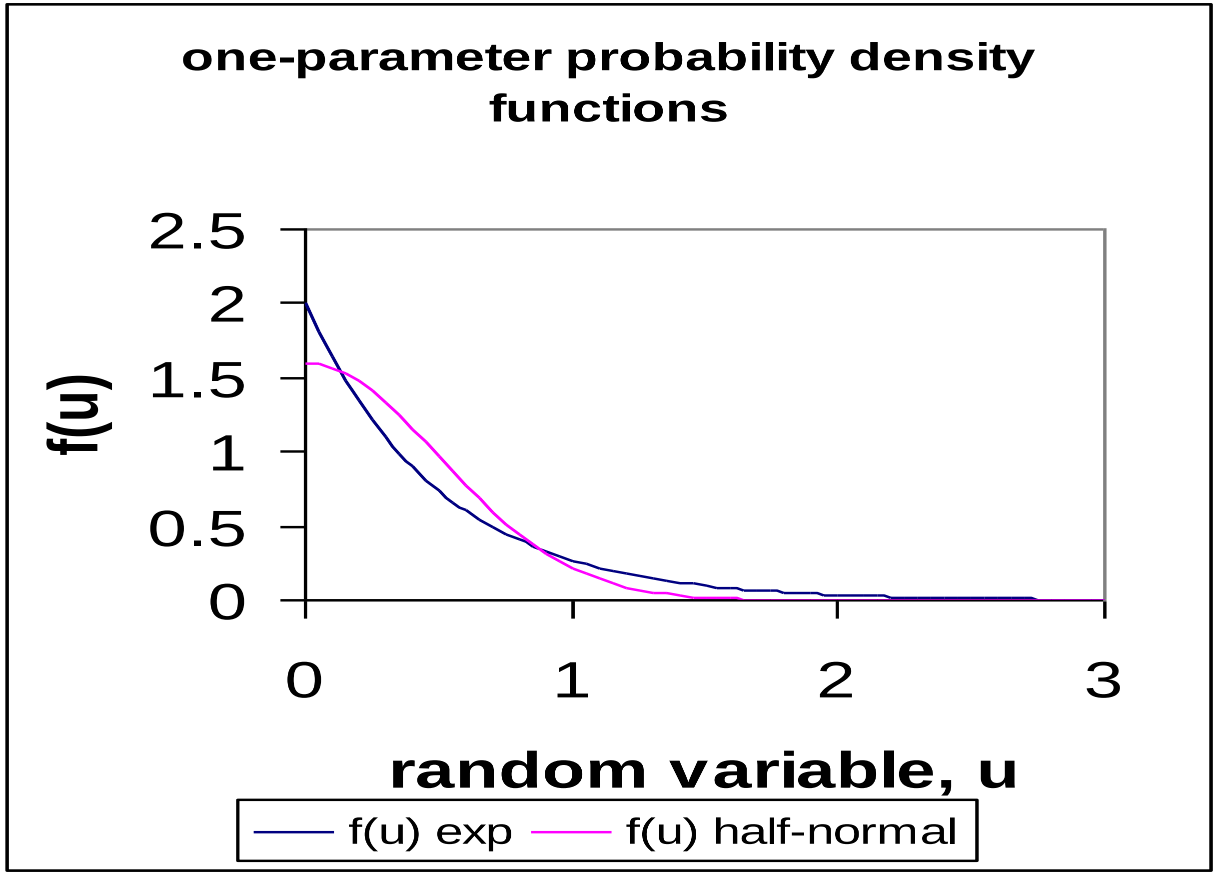
Likelihood function → Max Likelihood function in order to obtain the parameters

The marginal density function of e_i is

$$f_\varepsilon(\varepsilon_i) = \frac{2}{\sigma\sqrt{2\pi}} \phi\left(\frac{\varepsilon_i}{\sigma}\right)\left[\Phi\left(\frac{-\varepsilon_i\lambda}{\sigma}\right)\right].$$

where $\sigma = (\sigma_u^2 + \sigma_v^2)^{1/2}$, $\lambda = \sigma_u/\sigma_v$, and $\Phi(\cdot)$ and $\phi(\cdot)$ are the standard normal cumulative distribution and density functions. As $\lambda \to 0$ either $\sigma_v^2 \to +\infty$ or $\sigma_u^2 \to 0$, and the symmetric error component dominates the one-sided error component in the determination of ε. As $\lambda \to +\infty$ either $\sigma_u^2 \to +\infty$ or $\sigma_v^2 \to 0$ and the one-sided error component dominates the symmetric error component in the determination of ε. In the former case the stochastic cost frontier model collapses to an OLS cost function model with no variation in cost efficiency, whereas in the latter case the model collapses to a deterministic cost frontier model with no noise.

The exponential and half-normal assumption reflect the belief that larger values of inefficiency are less likely.



An input requirement function (Boyd, 2008);

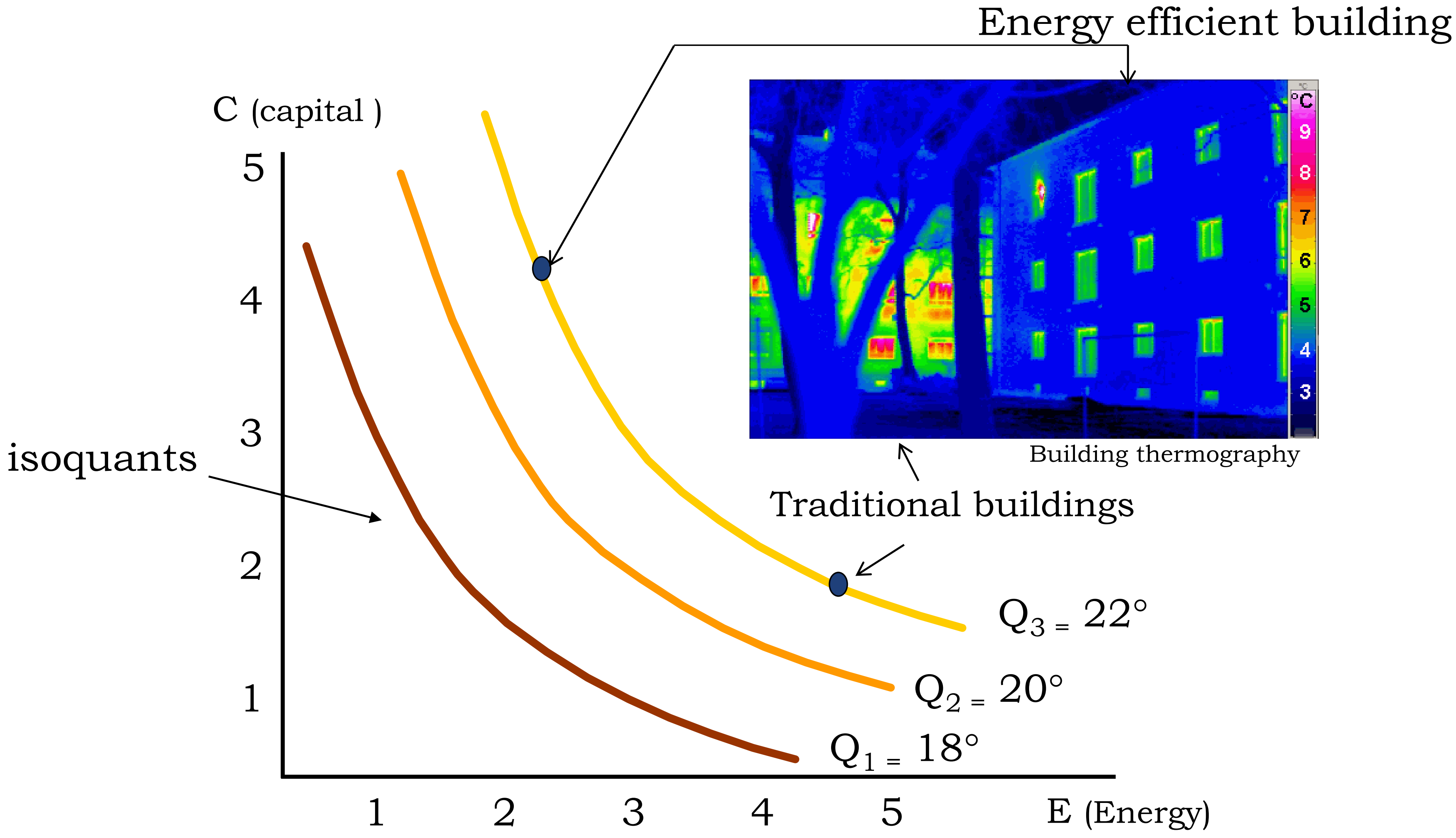
E=f(Y,K,LT)

$$
\begin{aligned}
&\ln E_{it} = \alpha + \boldsymbol{\beta}'\mathbf{x}_{it} + \varepsilon_{it}\\
&v_{it} \sim N[0, \sigma_v^2],\\
&u_{it} = |U_i|,\ U_{it} \sim N[0, \sigma_u^2],\\
&\varepsilon_{it} = v_{it} + u_{it},
\end{aligned}
$$

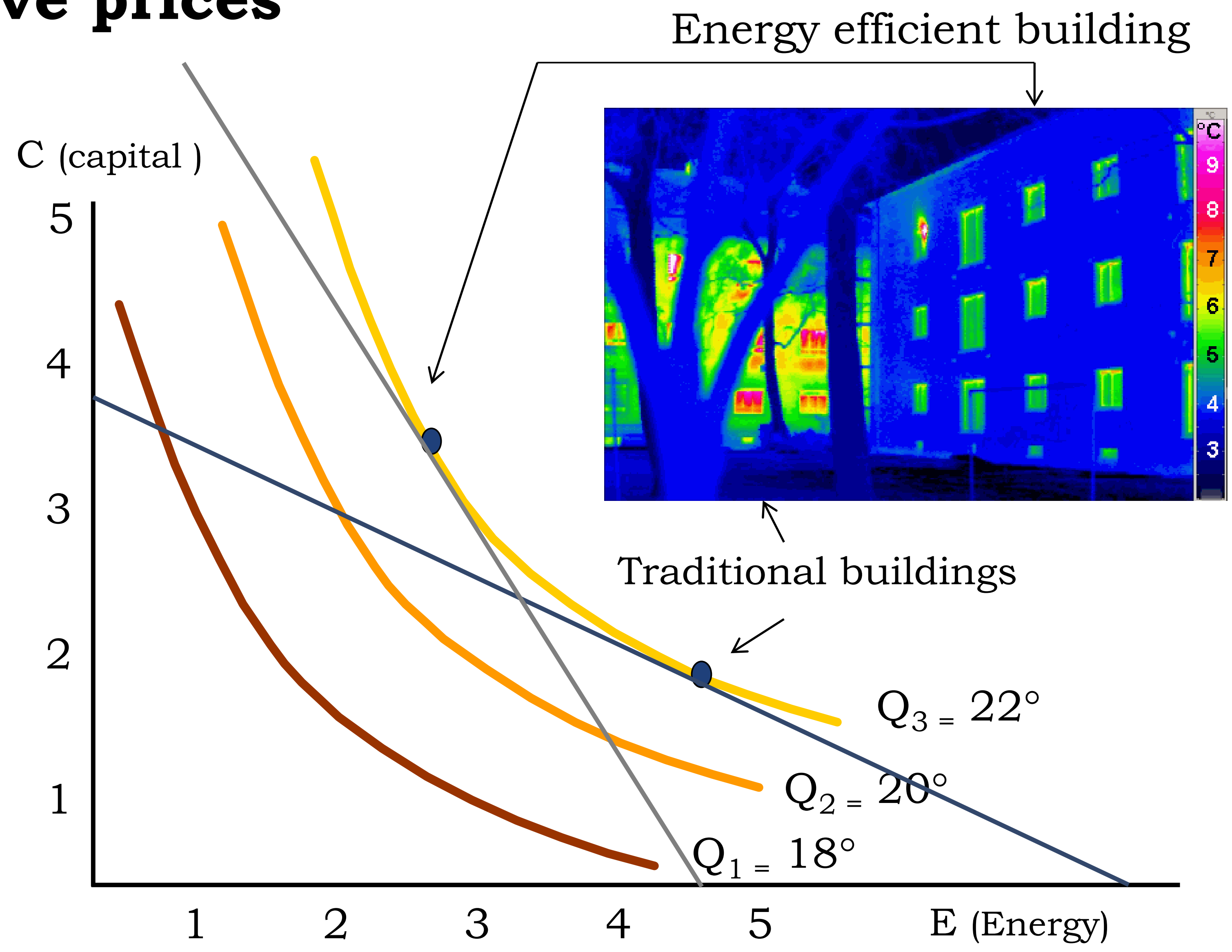
Another example of using an energy requirement function is Lin and Wang (2014) who estimate a translog specification as follows[32]:

$$
\begin{aligned}
\ln E_{it} = {} & \beta_0 + \beta_y \ln Y_{it} + \beta_k \ln K_{it} + \beta_l \ln L_{it} + \frac{1}{2}\beta_{yy}(\ln Y_{it})^2 + \frac{1}{2}\beta_{kk}(\ln K_{it})^2 + \frac{1}{2}\beta_{ll}(\ln L_{it})^2 + \\
& \beta_{kl}(\ln K_{it} * \ln L_{it}) + \beta_{yk}(\ln Y_{it} * \ln K_{it}) + \beta_{yl}(\ln Y_{it} * \ln L_{it}) + \beta_t T + \frac{1}{2}\beta_{tt} T^2 + \beta_{ty}(T * \ln Y_{it}) \\
& + \beta_{tk}(T * \ln K_{it}) + \beta_{tl}(T * \ln L_{it}) + v_{it} + u_{it}
\end{aligned}
$$

Case 1: production of an energy service (heating an apartment)



Different relative prices



A stocastic frontier energy demand function (Filippini and Hunt, 2011)

$$\begin{aligned}
\ln E_{it} &= \alpha + \boldsymbol{\beta}'\mathbf{z}_{it} + \varepsilon_{it} \\
v_{it} &\sim N[0, \sigma_v^2], \\
u_{it} &= |U_i|,\ U_{it} \sim N[0, \sigma_u^2], \\
\varepsilon_{it} &= v_{it} + u_{it},
\end{aligned}$$

The final group of examples estimate energy demand frontier functions. Filippini and Hunt (2011) estimated an energy demand frontier function for the whole economy with an unbalanced panel of 29 OECD countries over the period 1978 to 2006, which was extended and updated in Evans et al. (2013) for the period 1978 to 2008. The specification used being:

$$\begin{aligned}
e_{it} = {} & \alpha + \alpha^y y_{it} + \alpha^p p_{it} + \alpha^{pop} pop_{it} + \delta_t D_t + \alpha^C DCOLD_i + \alpha^R DARID_i \\
& + \alpha^a a_i + \alpha^I ISH_{it} + \alpha^S SSH_{it} + v_{it} + u_{it}
\end{aligned}$$

Possible distributions for $\mathbf{u}_i$

- Normal- Half-Normal model
- Normal-exponential model

- Two parameters distributions:
  ↳ Normal- Truncated-Normal model
  ↳ Normal- gamma model