Comparative energy efficiency of wastewater treatment plants based on economic foundations

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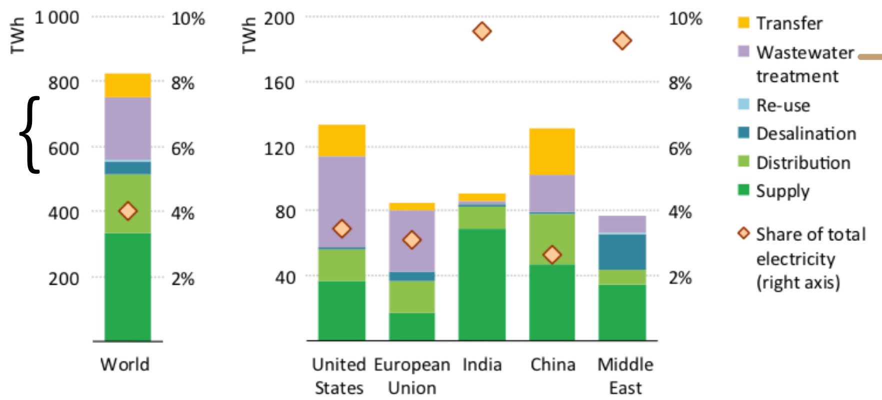
Introduction

- 4% of the global electricity consumption is used in the water sector.
  - Of the electricity consumed for water, around 30% is used for wastewater treatment.
  - energy considerations in the wastewater sector receive increasing attention from environmental/economic point of view, as announced by the European Commission in the proposal for a revision of the European Union drinking water directive.
  - Improving energy efficiency is a means to address these challenges.
  - Two main approaches used:
    - OLS method: the residuals are treated as measures of inefficiency.
    - Data Envelopment Analysis: it attributes all deviations from the frontier to inefficiency.
      - Stochastic Frontier Analysis (SFA) overcomes the above limitations since it is able to separate the inefficient component from the statistical noise.

There is a hidden lamp in our houses that is always on without us realizing it

~30% of the electricity consumed in the whole water cycle is for wastewater treatment

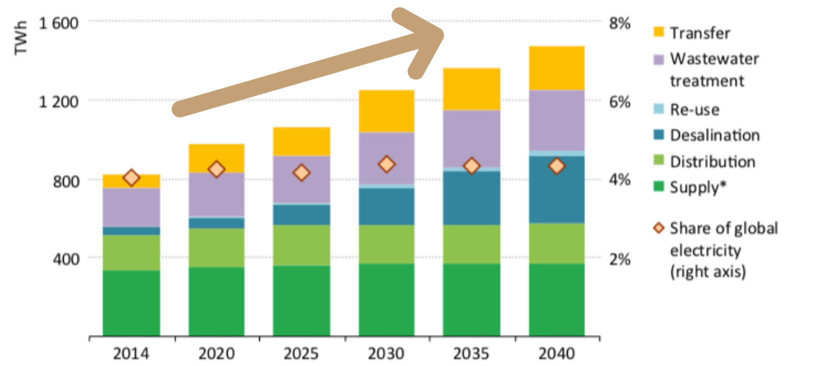


a 10W  per capita

The water sector accounted for 4% of global electricity consumption in 2014

Notes: Supply includes water extraction from groundwater and surface water, as well as water treatment. Transfer refers to large-scale inter-basin transfer projects.

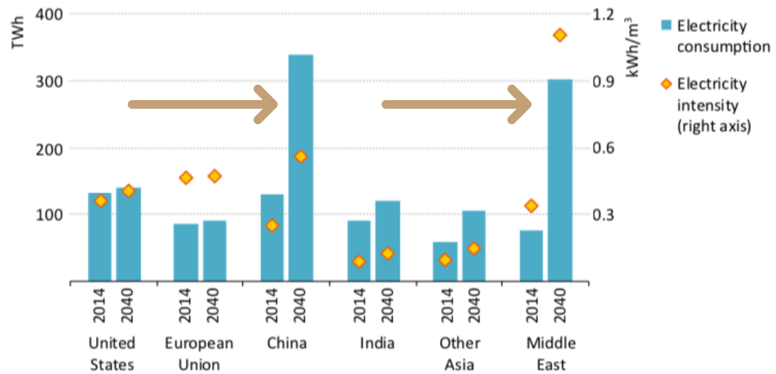
Sources: Luck, et al. (2015); Bijl, et al. (2016); Wada, et al. (2016); IEA analysis.



Electricity consumption in the water sector increases by 80% over the next 25 years

* Supply includes groundwater and surface water treatment.

Sources: Luck, et al. (2015); Bijl, et al. (2016); Wada, et al. (2016); IEA analysis.



Water use is projected to become more electricity intensive

Notes: Electricity intensity is calculated as total electricity consumption in the water sector, divided by total water withdrawals from agriculture, industry, power generation and municipal uses. Other Asia refers to other developing Asia.

Sources: Luck, et al. (2015); Bijl, et al. (2016); Wada, et al. (2016); IEA analysis.

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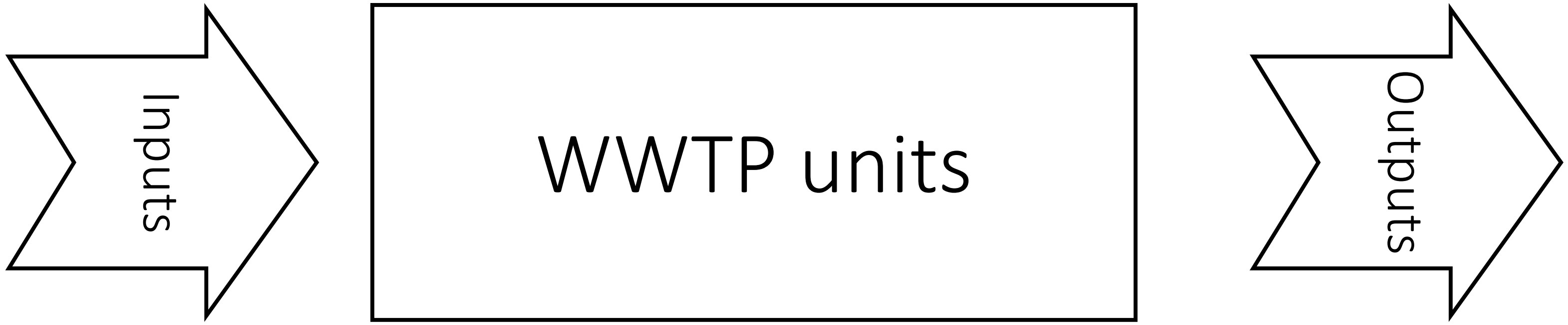
WWTP

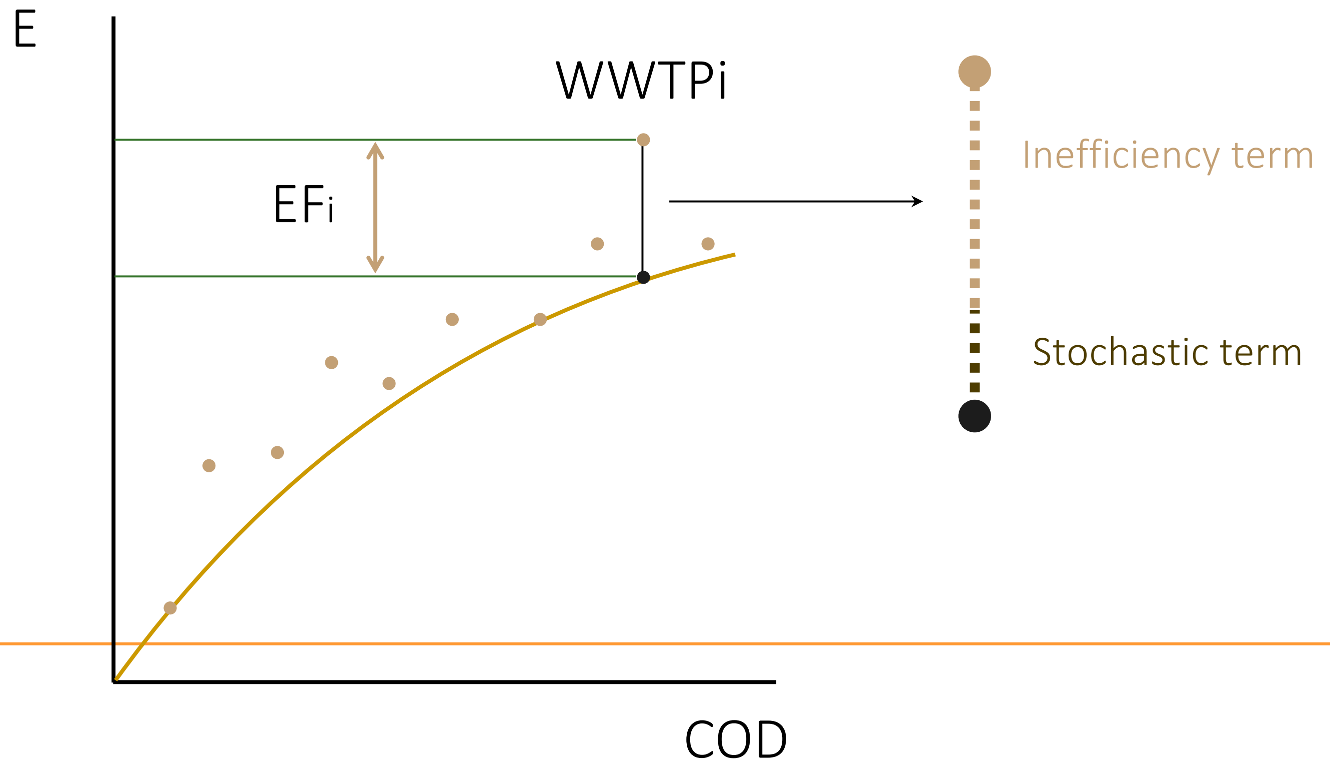


E = Electricity

COD = COD removed

Energy efficiency

The level of efficiency on the use of energy is normally based on the estimation of a frontier.



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Stochastic Frontier Analysis

$$E_{it} = \underbrace{\underbrace{\alpha_0 + f(X_{it};\beta)}_{\text{Deterministic frontier}} + \underbrace{v_{it}}_{\text{Error term}}}_{\text{Stochastic frontier}} - \underbrace{u_i}_{\text{Inefficiency term}}$$

Deterministic frontier

Inefficiency term

Stochastic frontier

Error term

$$u_i \geq 0$$
$$i = 1, \ldots N$$
$$t = 1, \ldots, T$$

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

Time invariant inefficiency

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

Low adoption of new energy efficient technologies

Inefficient use of equipment

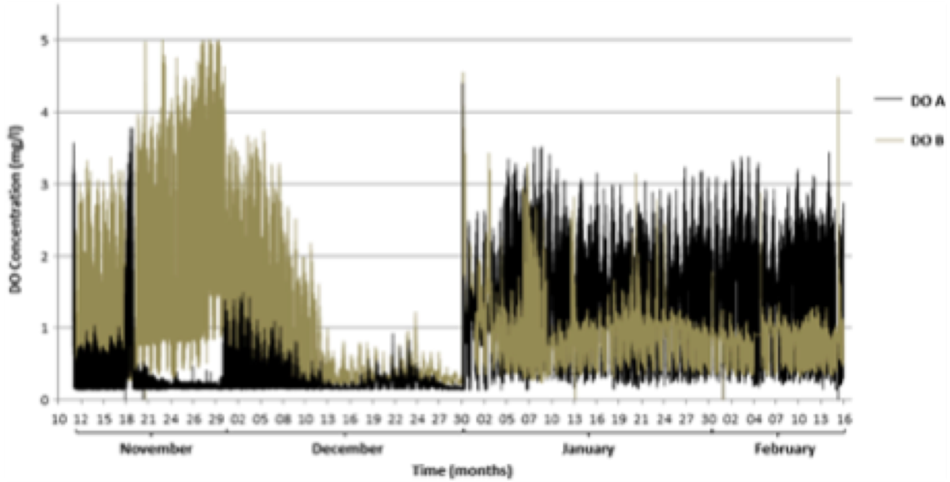

Fig. 1 DO concentration time profiles in tanks A and B

Based on previously used benchmarking methods, water utilities may decide to invest in new equipment and infrastructure, when instead the origins of inefficiency come from a non-optimal use of some equipment or vice versa

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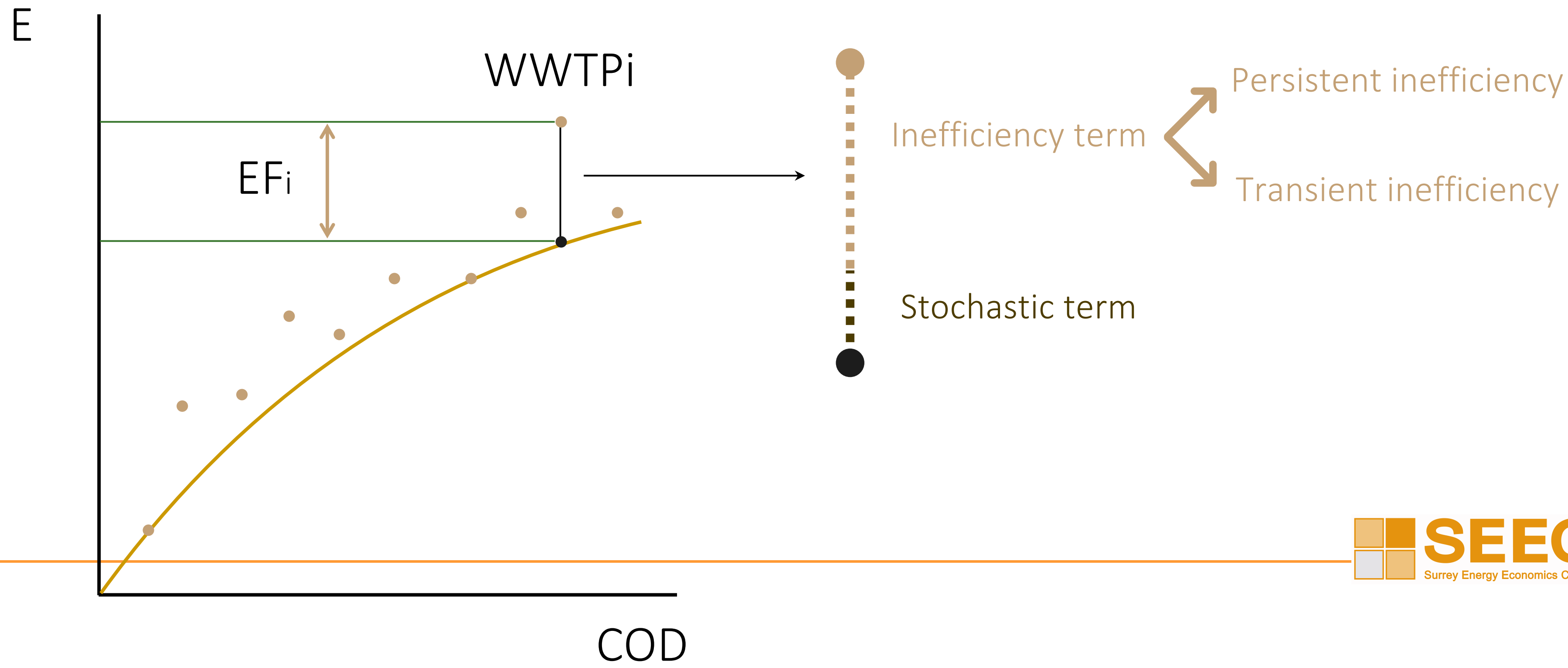
Energy efficiency: definition

The level of efficiency on the use of energy is normally based on the estimation of a frontier.



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WWTP energy demand model:

$$E_{it} = \alpha_0 + \alpha_P P_t + \alpha_{FLOW} FLOW_{it} + \alpha_{SIZE} SIZE_i + \alpha_{COD} COD_{it}$$

$$+ \alpha_{NH4} NH4_{it} + \alpha_{NO3} NO3_{it} + \alpha_{TEMP} TEMP_i$$

$$+ \alpha_{TECH} TECH_i + \alpha_{DEW} DEW_{it} + \varepsilon_{it}$$

where is energy consumption (kWh/day),
P is the real price of energy (CHF/kWh),
FLOW is the volume of wastewater treated (m^3/day),
SIZE is the size of the plant expressed as design flowrate (m^3/day),
COD, NH4 and NO4 are the concentrations of pollutants removed from wastewater (mg/L),
TEMP is the temperature (°C),
TECH is a dummy representing the technology of secondary treatment,
DEW is a dummy indicating whether the plant carries out also dewatering of sludge

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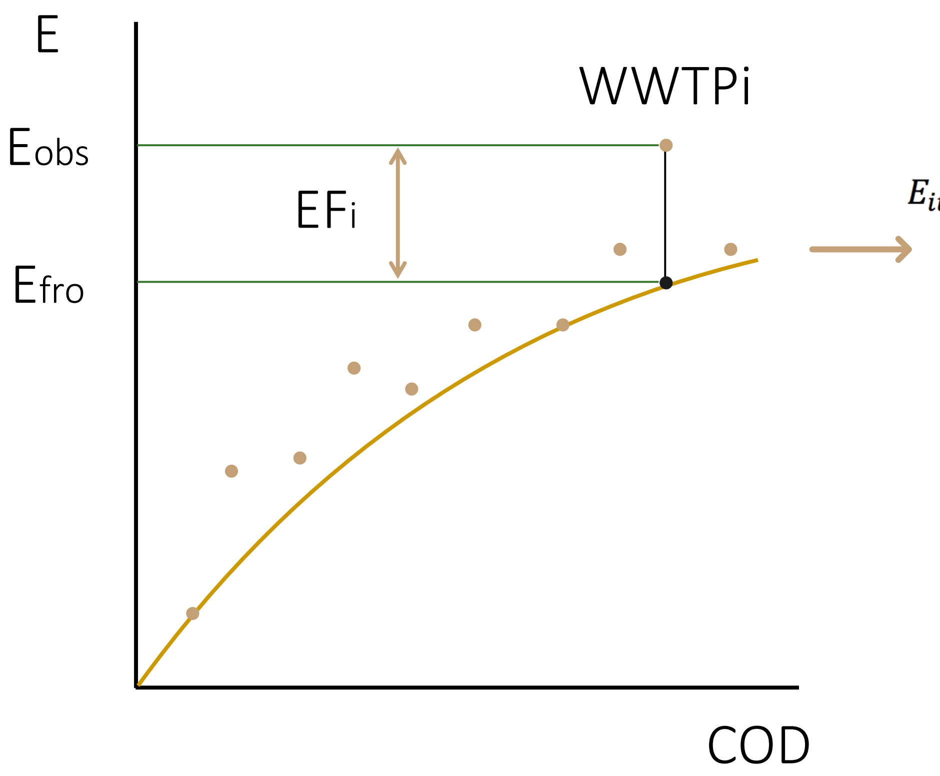
WWTP energy demand model

Input demand frontier function

(Filippini & Hunt, 2015)



Energy demand Frontier

the minimum amount of energy required to produce a given amount of wastewater treatment service

$$E_{it} = \alpha_0 + \alpha_P P_t + \alpha_{FLOW} FLOW_{it} + \alpha_{SIZE} SIZE_i + \alpha_{COD} COD_{it} + \alpha_{NH4} NH4_{it} + \alpha_{NO3} NO3_{it} + \alpha_{TEMP} TEMP_i + \alpha_{TECH} TECH_i + \alpha_{DEW} DEW_{it} + \varepsilon_{it}$$

Energy efficiency

measures the ability of a WWTP to minimize the energy consumption, given a level of wastewater treatment service

Econometric specifications of the SFA models

$$Model\ I: E_{it} = \alpha_0 + f(X_{it};\beta) + v_{it} + \alpha_i$$

noise (v_{it}); (time-invariant) inefficiency (α_i)

(Schmidt & Sickles, 1984)

$$Model\ II: E_{it} = \alpha_0 + f(X_{it};\beta) + v_{it} - u_i - \tau_{it}$$

noise (v_{it}); persistent inefficiency (u_i); transient inefficiency (τ_{it})

(Kumbhakar & Heshmati, 1995)

$$Model\ III: E_{it} = a_0 + f(X_{it};\beta) + v_{it} + \mu_i - \eta_i - u_{it}$$

noise (v_{it}); unobserved heterogeneity (μ_i); persistent inefficiency (η_i); transient inefficiency (u_{it})

(Kumbhakar, Lien, & Hardaker, 2014)

also allows to study the determinants of persistent inefficiency

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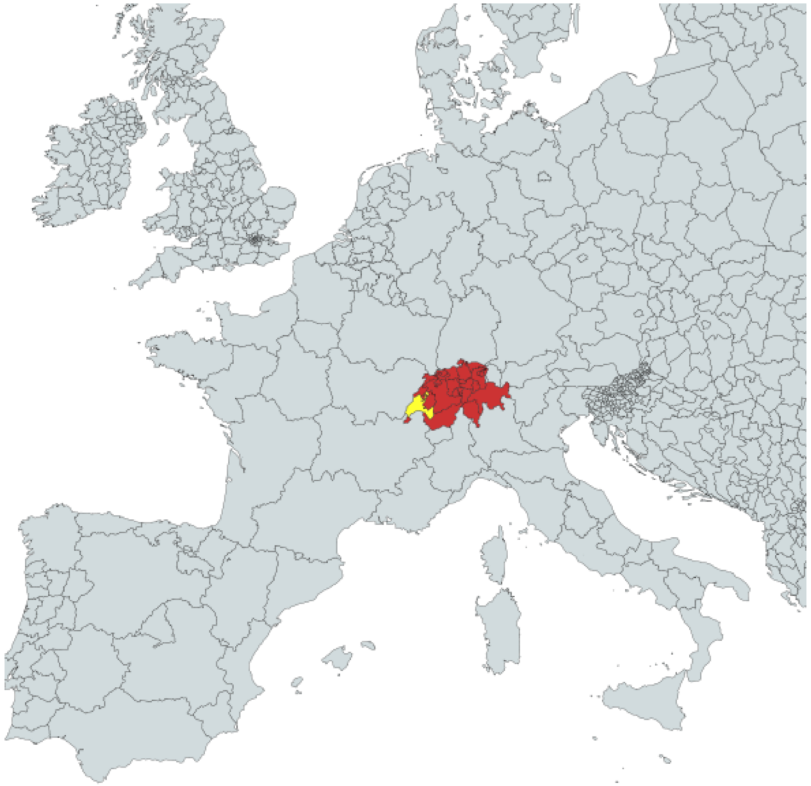
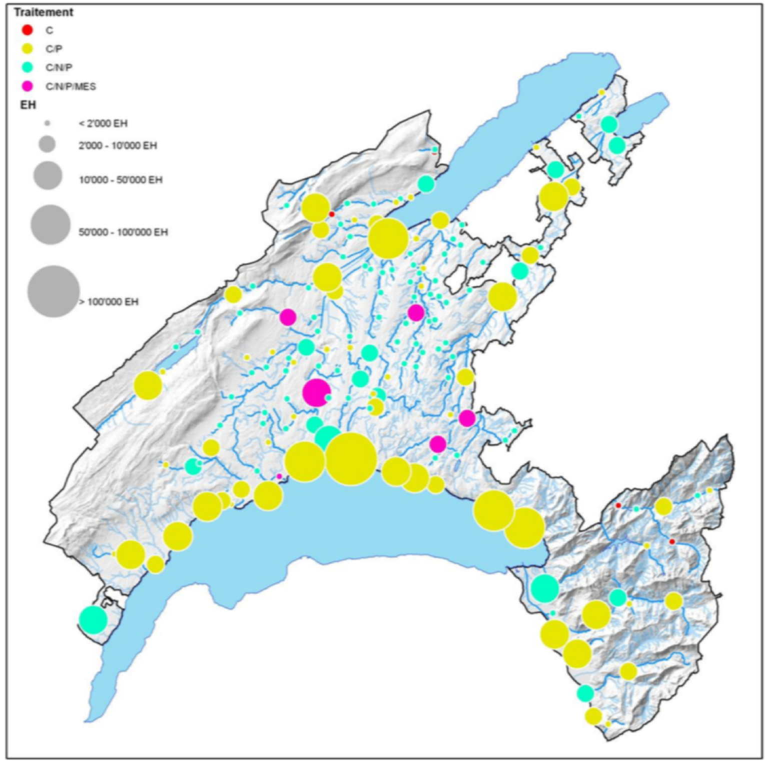
Data





Stations d'épuration vaudoises selon leurs capacités et niveaux de traitement
C = carbone, P = phosphore, N = azote, MES = matières en suspension (normes renforcées)

- We use a database of the Directorate General for the Environment (DGE) of the canton of Vaud (Switzerland)
- Unbalanced panel data of 183 WWTPs
- 9.3% of the Swiss population
- Observation period 2001-2015 (2136 observations)

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Data

Variable	Definition	Obs.	Mean	SD	Min	Max
E	Electricity consumption (kWh/day)	2136	596	2685.7	1.4	36060.0
FLOW	Wastewater flowrate (m^3/day)	2136	1792.6	8435.5	4.0	122889.0
SIZE	Design wastewater flowrate (m^3/day)	2136	3576.8	17399.0	17.0	206250.0
CODREM	COD removal (mgCOD/L)	2136	437.5	229.0	20.0	1362.0
NH4REM	NH4 removal (mgN/L)	2136	19.3	14.7	0.0	80.3
NO3REM	NO3 removal (mgN/L)	2136	7.9	10.4	0.0	63.4
TEMP	Temperature (°C)	2136	8.7	1.3	4.3	12.2
PRICE	Real electricity price (CHF/kWh)	2136	0.13	0.91	0.12	0.16
CONSTR	Year of plant construction (year)	2136	1980.7	10.6	1961.0	2014.0
TECH (Ref = CAS)	Secondary treatment technology					
MH-CAS	Medium/High load Conventional Activated Sludge	449	/	/	/	/
RBC	Rotating Biological Contactor	55	/	/	/	/
TF	Trickling Filter	346	/	/	/	/
TF-CAS	Trickling Filter - Conventional Activated Sludge	8	/	/	/	/
FBR	Fluidized Bed Reactor	33	/	/	/	/
FBR-CAS	Fluidized Bed Reactor - Conventional Activated Sludge	20	/	/	/	/
DEWATER (Ref = NO)	Sludge dewatering					
YES	Presence of sludge dewatering	955	/	/	/	/

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Estimated energy demand model

Parameter	Coefficient
Constant	0.0933***
FLOW	0.3781***
SIZE	0.5396***
CODREM	0.0908***
NH4REM	0.0519***
NO3REM	-0.0467***
TEMP	0.0579**
PRICE	-0.0081*
DEWATER (ref = NO)	
YES	0.0649***
TECH (ref = CAS)	
MH-CAS	-0.0981
RBC	-0.4333***
TF	-0.5217***
TF-CAS	-0.1015
FBR	0.1746
FBR-CAS	-0.1087
Persistent inefficiency determinants, model III	
Constant	-3.7943***
CONSTR	-0.4408***
Variance parameters for the compound error	
sigma u	0.2914***
sigma e	0.1802***
rho	0.7232***

→ pumping (FLOW)

→ RAS, mixers, sed. tanks (SIZE)

} → treatment intensity (CODREM, NH4REM, NO3REM)

→ oxygen transfer (TEMP)

→ incentive (PRICE)

→ sludge dewatering (DEWATER)

} → process configuration (TECH)

→ year of plant construction (CONSTR)

} → efficiency estimation (variance parameters)

*** Significant at 1% level
** Significant at 5% level
* Significant at 10% level

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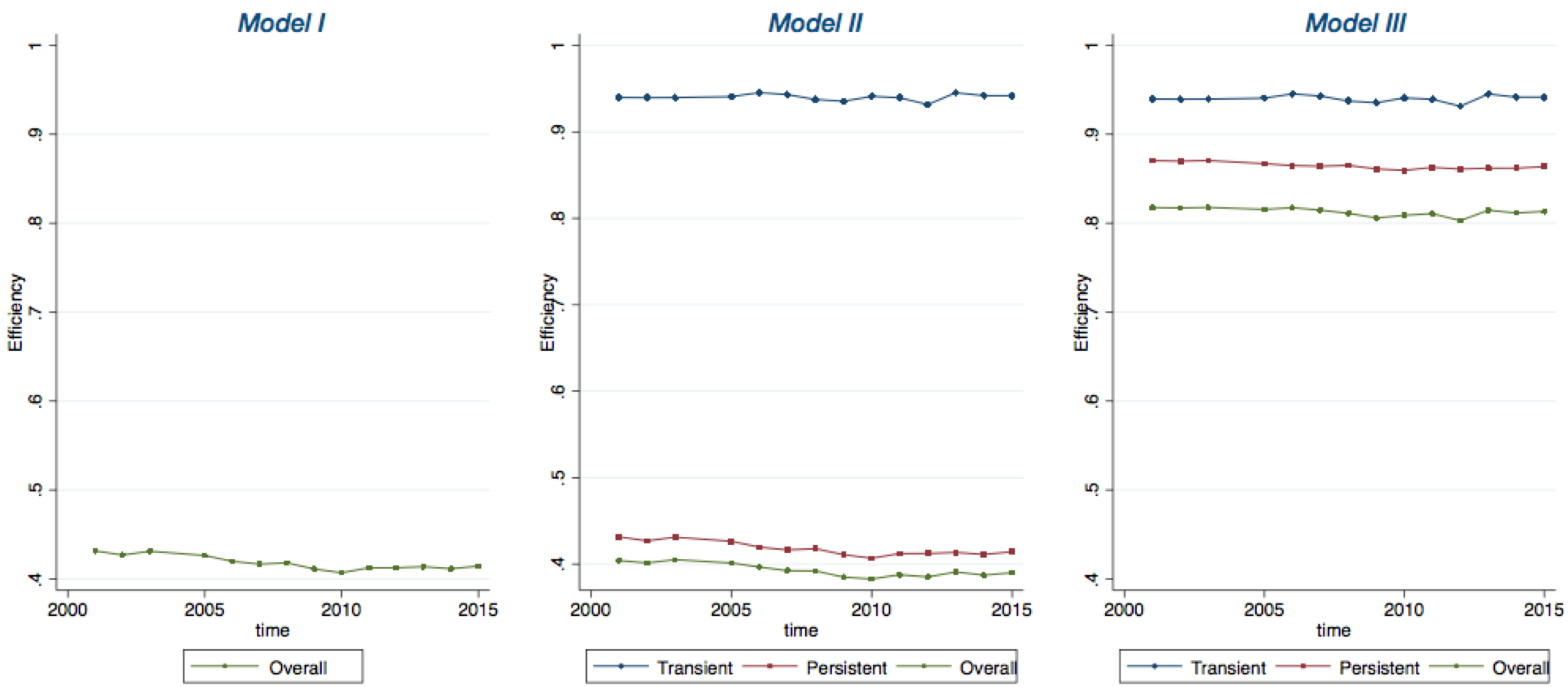
Estimated average efficiency over time

Overall efficiency = transient efficiency x persistent efficiency



- There exists a large room for improvement
- Persistent inefficiency is more severe than transient inefficiency
- The majority of the persistent inefficiency is actually unobserved heterogeneity

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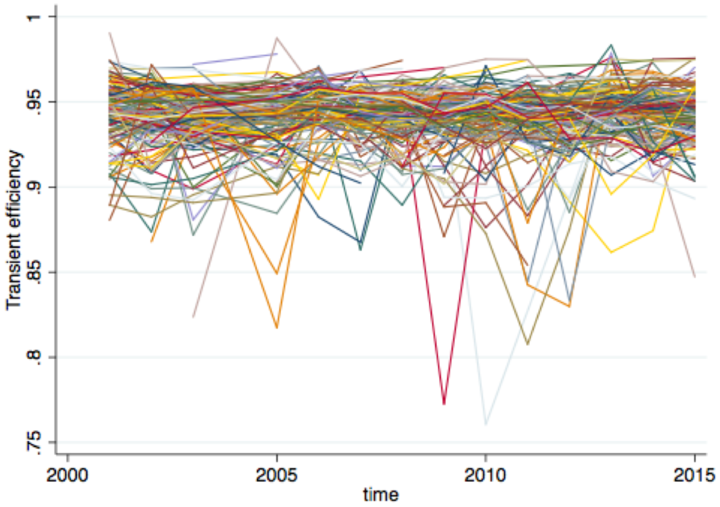
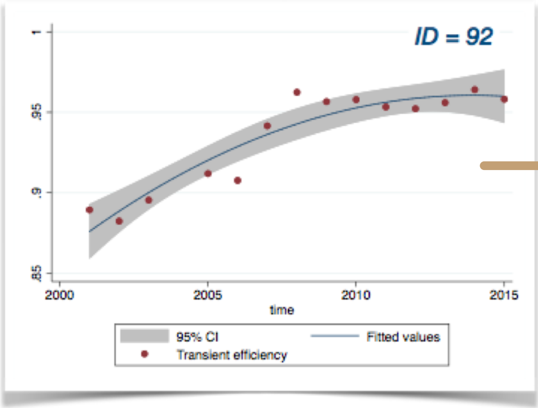
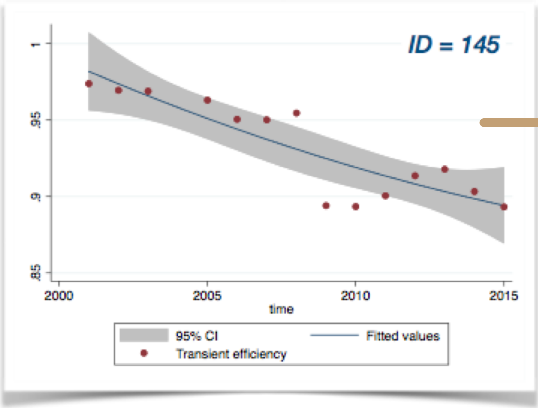
Transient efficiency (over time)







Optimal evaluation of monitoring data

Adaption of wrong operational strategies, due to poor data analysis, too infrequent sampling, inadequate controller settings

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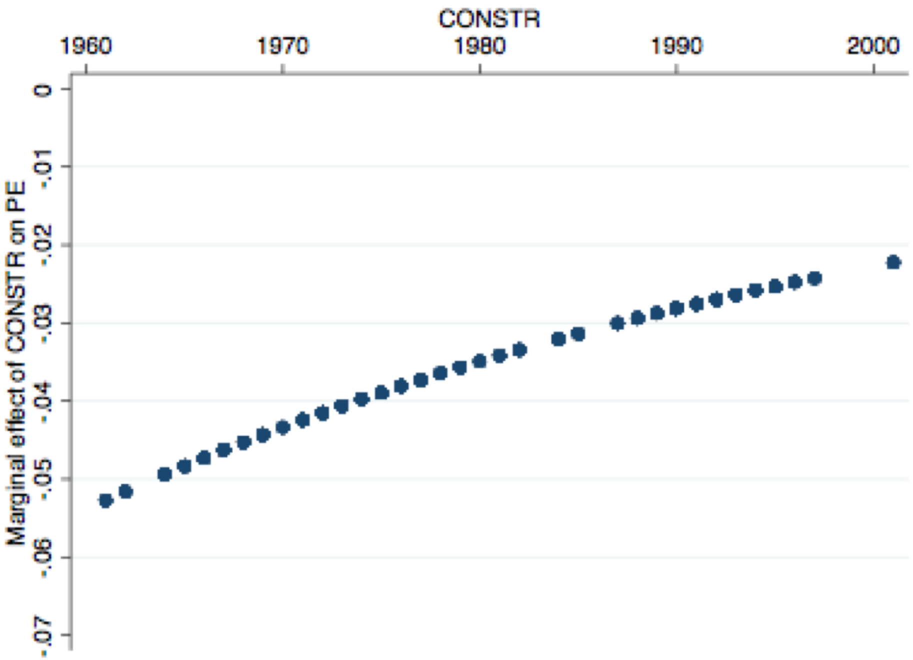
Impact of technical progress (construction year) on persistent efficiency



- Renovating a plant effectively decreases the persistent inefficiency
- The relation between technical progress and persistent inefficiency is not linear and depends on the value CONSTR
- The convenience of renewing is highest for the oldest systems having the ability to eliminate up to 5% of their persistent inefficiency

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Economies of scale

Economies of output density measures the reaction of energy demand to an increase in output (i.e. the amount of treated wastewater)

$$E_{OD} = \left(\frac{\partial \ln E}{\partial \ln FLOW}\right)^{-1} = \frac{1}{0.38} = 2.6$$

For each 2.6% increase in the volume of WW the energy demand increases by only 1%

$$E_S = \left(\frac{\partial \ln E}{\partial \ln FLOW} + \frac{\partial \ln E}{\partial \ln SIZE}\right)^{-1} = \frac{1}{0.38 + 0.54} = 1.1$$

Increasing the size (including the volume of WW) by 1.1% will increase % the energy demand by 1

Economies of scales not only raises the volume of wastewater received by the plant, but to the same proportion also the design flow (i.e. by scaling up all the equipment as well as reactors volumes)

	Small WWTPs	**Medium WWTPs**	**Large WWTPs**
E_{OD}	2.50	3.57	1.85
E_S	1.30	1.59	1.23

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Conclusions

- The current data-rich, information-poor condition is a general problem in the wastewater sector.
- Borrowing methods from other fields and the use of panel data allowed the successful transformation of data into useful information.
- Distinguish between persistent and transient inefficiency is essential to deduce appropriate energy diagnosis in order to make inefficient WWTPs efficient.
- The level of energy efficiency of equipment influences the demand for energy. As a consequence, technological innovation can induce a reduction of energy consumption provided that the equipment are used in an efficient way

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