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.

\[ \{ \text{~30% of the electricity consumed in the whole water cycle is for wastewater treatment} \} \]

a 10W per capita

\[ \text{~30% of the electricity consumed in the whole water cycle is for wastewater treatment} \]
WWTP

Inputs

E = Electricity

Outputs

COD = COD removed
Energy efficiency

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

If you can not measure it, you can not improve it.*
Lord Kelvin
*kind of, sort of

Diagram:
- E vs COD
- WWTPi
- Inefficiency term
- Stochastic term

SEEC
Survey Energy Economics Centre
Stochastic Frontier Analysis

\[ E_{it} = \alpha_0 + f(X_{it}; \beta) + \nu_{it} - u_i \]

- **Deterministic frontier**
- **Stochastic frontier**
- **Inefficiency term**
- **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*
Inefficiency in the use of energy (waste of energy) may due to:

- Low adoption of new energy efficient technologies
- Inefficient use of equipment

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.
Energy efficiency: definition

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![Graph showing energy efficiency](image)

- **COD**
- **EF**
- **Inefficiency term**
- **Persistent inefficiency**
- **Transient inefficiency**
- **Stochastic term**

**E**

**WWTP**

**EF**

**COD**
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 \( E \) 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.
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:**

\[ E_{it} = \alpha_0 + f(X_{it}; \beta) + \nu_{it} + \alpha_i \]

(Schmidt & Sickles, 1984)

- Noise
- (time-invariant) inefficiency

**Model II:**

\[ E_{it} = \alpha_0 + f(X_{it}; \beta) + \nu_{it} - u_i - \tau_{it} \]

(Kumbhakar & Heshmati, 1995)

- Noise
- Persistent inefficiency
- Transient inefficiency

**Model III:**

\[ E_{it} = \alpha_0 + f(X_{it}; \beta) + \nu_{it} + \mu_i - \eta_i - u_{it} \]

(Kumbhakar, Lien, & Hardaker, 2014)

- Noise
- Unobserved heterogeneity
- Persistent inefficiency

Also allows to study the determinants of persistent inefficiency.
Data

- 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)
## Data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Obs.</th>
<th>Mean</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
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</thead>
<tbody>
<tr>
<td>E</td>
<td>Electricity consumption (kWh/day)</td>
<td>2136</td>
<td>596</td>
<td>2685.7</td>
<td>1.4</td>
<td>36060.0</td>
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<td>FLOW</td>
<td>Wastewater flowrate (m³/day)</td>
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<td>1792.6</td>
<td>8435.5</td>
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<td>122889.0</td>
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<td>SIZE</td>
<td>Design wastewater flowrate (m³/day)</td>
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<td>17399.0</td>
<td>17.0</td>
<td>206250.0</td>
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<td>CODREM</td>
<td>COD removal (mgCOD/L)</td>
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<td>437.5</td>
<td>229.0</td>
<td>20.0</td>
<td>1362.0</td>
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<td>Temperature (°C)</td>
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<td>1.3</td>
<td>4.3</td>
<td>12.2</td>
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<td>PRICE</td>
<td>Real electricity price (CHF/kWh)</td>
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<td>0.13</td>
<td>0.91</td>
<td>0.12</td>
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<td>CONSTR</td>
<td>Year of plant construction (year)</td>
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<td>1980.7</td>
<td>10.6</td>
<td>1961.0</td>
<td>2014.0</td>
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<tr>
<td>TECH (Ref = CAS)</td>
<td>Secondary treatment technology</td>
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<td></td>
<td></td>
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<tr>
<td>MH-CAS</td>
<td>Medium/High load Conventional Activated Sludge</td>
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<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
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<tr>
<td>RBC</td>
<td>Rotating Biological Contactor</td>
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<td>TF</td>
<td>Trickling Filter</td>
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<td>/</td>
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<tr>
<td>TF-CAS</td>
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<tr>
<td>FBR-CAS</td>
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<td>/</td>
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<td>DEWATER (Ref = NO)</td>
<td>Sludge dewatering</td>
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<td></td>
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<td>YES</td>
<td>Presence of sludge dewatering</td>
<td>955</td>
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<td>/</td>
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</table>
## Estimated energy demand model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constant</strong></td>
<td>0.0933***</td>
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<tr>
<td>FLOW</td>
<td>0.3781***</td>
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<tr>
<td>SIZE</td>
<td>0.5396***</td>
</tr>
<tr>
<td>CODREM</td>
<td>0.0908***</td>
</tr>
<tr>
<td>NH4REM</td>
<td>0.0519***</td>
</tr>
<tr>
<td>NO3REM</td>
<td>-0.0467***</td>
</tr>
<tr>
<td>TEMP</td>
<td>0.0579**</td>
</tr>
<tr>
<td>PRICE</td>
<td>-0.0081*</td>
</tr>
<tr>
<td>DEWATER (ref = NO)</td>
<td></td>
</tr>
<tr>
<td>YES</td>
<td>0.0649***</td>
</tr>
<tr>
<td>TECH (ref = CAS)</td>
<td></td>
</tr>
<tr>
<td>MH-CAS</td>
<td>-0.0981</td>
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<tr>
<td>RBC</td>
<td>-0.4333***</td>
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<tr>
<td>TF</td>
<td>-0.5217***</td>
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<td>FBR</td>
<td>0.1746</td>
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<tr>
<td>FBR-CAS</td>
<td>-0.1087</td>
</tr>
</tbody>
</table>

### 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***

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

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**process configuration**

- pumping
- RAS, mixers, sed. tanks
- treatment intensity
- oxygen transfer
- incentive
- sludge dewatering

**efficiency estimation**

- year of plant construction
Estimated average efficiency over time

Overall efficiency = transient efficiency \times 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
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
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.
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)

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

<table>
<thead>
<tr>
<th></th>
<th>Small WWTPs</th>
<th>Medium WWTPs</th>
<th>Large WWTPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{OD}$</td>
<td>2.50</td>
<td>3.57</td>
<td>1.85</td>
</tr>
<tr>
<td>$E_{S}$</td>
<td>1.30</td>
<td>1.59</td>
<td>1.23</td>
</tr>
</tbody>
</table>
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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