A coupled energy & air quality model for lowest cost energy solutions, respecting air quality constraints: development and initial results

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NOAA SEMINAR - NCWCP Conference Center College Park
Introduction to energy – air quality modeling

The model

An illustrative example

Results
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TUDOR Modeling Group – Research snapshot

Integrated assessment: Energy-AQ

Energy model: ETEM Luxembourg

Emission Allocation

Optimization: OBOE

Air quality model: AUSTAL2000-AYLTP

Integrated assessment: Impact

Bayesian risk (atmospheric forecasting)

AQ

Energy projections

Geospatial analysis
Air pollution – a major concern

- The London smog disaster 1952, brought attention to the damaging effects of air pollution.

- There is a negative relation of air pollution with human health, resulting in an increase of morbidity and mortality.
  
  [Ström et al., 1994; Solè et al., 2007; West et al., 2007; Laaidi et al., 2011; Rückerl et al., 2011; Tzivian, 2011].

- “Urban outdoor air pollution is estimated to cause 1.3 million deaths worldwide per year.” [World Health Organization, 2011].
A need for integrated solutions

“Indeed air pollutant concentrations are still too high and harm our health and the ecosystems we depend on.”  

Ozone ($O_3$) is one of the most problematic and harmful pollutants. Exposure to $O_3$ has generally not decreased since 2001.  

European legislation on air quality has been developed and is becoming more and more strict.

“European policies and measures increasingly seek to maximise co-benefits, managing air pollutant and greenhouse gas emissions at the least cost to society.”  
NOx + VOC + Heat & Sunlight = Ozone

Ground-level or “bad” ozone is not emitted directly into the air, but is created by chemical reactions between NOx and VOCs in the presence of heat & sunlight.

Emissions from industrial facilities and electric utilities, motor vehicle exhaust, gasoline vapors, and chemical solvents are some of the major sources of oxides of nitrogen (NOx) and volatile organic compounds (VOC).
Some models explore solutions via simulation – e.g. (EC4MACS)
Introduction / Motivation

The model (Energy-emissions / Air Quality)

An illustrative example

Results
The integrated assessment model – the LEAQ model

Energy Technology Environmental Model - ETEM

Energy model: ETEM Luxembourg

GIS / geospatial analysis tools

http://crteweb.tudor.lu/leaq/
The ETEM model

Reference Energy System of Luxembourg

**Energy Model**
- Dynamic linear optimization
- End-use demands
- Future technologies
- Energy prices evolution
- Total energy system cost
- Energy policy assessment
- GHG (CO₂, CH₂, N₂O)
- Air pollutants (NOₓ, VOC)
ETEM (Energy Technology Environmental Model)

- ETEM model (http://www.ordecsys.com)
- Implementation of MARKAL/TIMES in GMPL (LP)
- Energy system of Luxembourg (≈ 100’000 rows/columns)
- Time horizon: 9 periods of 5 years (2005–2050)
- Minimize the total discounted energy cost s.t.
  - the demands in energy services are satisfied,
  - the commodity flows balance is respected;

$$\min_{x} \{c'x \mid Ax = b, x \geq 0\}$$
The ETEM model

param nb_periods  >=1;
param period_length >=1;  # expressed in year.

set T := 1..nb_periods;  # time periods.
set L;  # localization
set S;  # slice periods
set P;  # processes
set C;  # commodities
set DEM within C;  # useful demands
set IMP within C;  # imported commodities
set EXP within C;  # exported commodities
set FLOW;  # commodities groups labels
set FLOW_IN{P} within FLOW;  # incoming flows
set FLOW_OUT{P} within FLOW;  # outcoming flows
set C_ITEMS{FLOW} within C;  # set of commodities
set P_MAP{L} within P;  # localization of processes

Plus about 350 more lines
The ETEM data

data;

# set of time slices
set S:=
WD  # Winter Day
WN  # Winter Night
SD  # Summer Day
SN  # Summer Night
ID  # Intermediate Day
IN;  # Intermediate Night

# set of localisations (cities)
set L:=
LUXEMBOURG
HAUTSURE
CADIOM;

# set of processes
set P:=
    # Electricity Industrial
    # existing technology
I11  # Electrical appliances
I13  # El. savings industrial 2
I14  # El. savings industrial 3
I15  # El. savings industrial 4
I1A  # El. savings heat pump
I1B  # El. savings clim/air
I1C  # El. savings cold
I1I  # El. savings compressor
I1J  # El. savings pumps
I1K  # El. savings fax/photocopy
    # new technology
    # LTH Industrial Area
IA1  # Electric

Plus about 2500 more lines
### ETEM Luxembourg

#### ACTIONS
- Browse all
- New commodity
- Duplicate
- Delete

#### COMMODITY
- **Name**: TRA-RD-CAR
- **Description**: Road Transport - Cars
- **Category**: Demand

#### FLOWS
- Not consumed.
- Produced by 78 technologies:

#### PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Time slice</th>
<th>Year</th>
<th>Value</th>
<th>Source</th>
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<td>CRTE estimates [Mpkm]</td>
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<td>2009</td>
<td>1.01</td>
<td>CRTE estimates [conso carburant ménages]</td>
<td></td>
</tr>
</tbody>
</table>

**Follow demand driver**: statec-population

**Default demand elasticity**: 1

Emissions

Sectoral emissions $\bar{e}$ are distributed over space and time to provide emissions rates at sources using land-use maps and spots.

\[ \bar{e} = \int_{S \times T} E(t, s) ds dt \]
The air quality model

AOT: Average Over Threshold (60 ppb)

\[ AOT(\bar{e}) = \frac{1}{|S|} \frac{1}{t} \int_{S \times T} C_{O_3}(t, s; \bar{e}) ds dt \]

Calculation time

Emission allocation + AYLTP + AOT calculation = 5 min
The air quality model – example of dynamics in a Lagrangian model

Brownian motion

\[ x = \hat{x} + d(\hat{x}) + s \]

\( \hat{x} \) particle location at time \( t + \tau \)

\( d \) deterministic displacement \( \tau V(\hat{x}) \),

\( s \) stochastic displacement with distribution function

\( V \) particle velocity

Other dynamics included
- Brownian diffusion
- Brownian turbulence
The air quality model – dynamics

A cloud of 1000 simulation particles emitted all at the same time at the height 100 m, shown 80 seconds after emission (left part of the picture) and 240 seconds after emission (right part). Note the effects of wind shear.
The air quality model

\[
AOT = \frac{1}{T \times S} \int_0^T \int_S \max(0, c(t, x; \bar{e})) \, ds \, dt
\]

Day: July 19th 2006

- high ozone concentration day
- ETEM emissions calibrated for 2006

\( O_3 \, \mu g \, m^{-3} \)
The integrated assessment model

Energy Technology
Environmental Model

Energy model: ETEM Luxembourg

Optimization: OBOE

GIS / geospatial analysis tools

http://crteweb.tudor.lu/leaq/
The coupled model – combining ETEM and AQ with OBOE

Cost minimization problem:

\[
\min \{ \gamma(e) : AOT(e,p) \leq AOT_{\text{max}} \}
\]

\[
\gamma = \min \{ c'x \mid Ax = b, \ x \geq 0 \}
\]

\( p \) = pollution (\( O_3 \) concentration in ppb) level \hspace{0.5cm} \text{decision variable}

\( e \) = emissions (tonnes per year) \hspace{0.5cm} \text{decision variable}

AOT = Accumulated Ozone exposure over a Threshold
Introduction / Motivation

The model (Energy-emissions / Air Quality)

An illustrative example

Results
Example – a very simple economy

Car of type 1 – inexpensive, heavily polluting, maximum $N_1$

Car of type 2 – expensive, lightly polluting, maximum $N_2$
Supply & demand – for 2 types of cars

Car – type 1

Car – type 2
A short overview of convex optimization

Energy Costs

Optimal cost without AQ constraints

number of cars (of type 1)

cost

demand

N1
A short overview of convex optimization

Convex Bounds due to non-linear AQ constraints

Energy Costs

Emission constraints

Optimal cost with AQ constraints

Optimal cost without AQ constraints

cost

demand

number of cars (of type 1)
A short overview of convex optimization

![Convex Cost Curve Diagram]
A short overview of convex optimization

Bounds to cost

Energy Costs

f(x) = cost curve

Bounds (min, max cars of type i)

Select a starting point

number of cars (of type 1)
A short overview of convex optimization

\[ f(x) = \text{cost curve} \]

Bounds to cost

Energy Costs

Simulated cost

number of cars (of type 1)

Bounds (min, max cars of type i)

Select a starting point
A short overview of convex optimization

Energy Costs

\[ f(x) = \text{cost curve} \]

number of cars (of type 1)
A short overview of convex optimization

Energy Costs

Sub-gradient (support plane)

Simulated cost

number of cars (of type 1)
A short overview of convex optimization

Energy Costs

number of cars (of type 1)

Sub-gradient (support plane)

Acceptable region (where solution must be found)
A short overview of convex optimization

Energy Costs

Sub-gradient (support plane)

Acceptable region (where solution must be found)

Geometric center of acceptable region

number of cars (of type 1)
A short overview of convex optimization

Sub-gradient (support plane)

Acceptable region (where solution must be found)

2nd suggested point

Geometric center of acceptable region

Energy Costs

number of cars (of type 1)
A short overview of convex optimization

- Sub-gradient (support plane)
- Acceptable region (where solution must be found)
- Geometric center of acceptable region
- Energy Costs
- Number of cars (of type 1)
- 2nd suggested point
- 2nd Sub-gradient
A short overview of convex optimization

- Sub-gradient (support plane)
- Acceptable region (where solution must be found)
- Geometric center of acceptable region
- New lower bound
- Number of cars (of type 1)

Energy Costs

- 2nd suggested point
- 2nd Sub-gradient
A short overview of convex optimization

Energy Costs

Sub-gradient (support plane)

Acceptable region (where solution must be found)

Geometric center of acceptable region

New lower bound

number of cars (of type 1)
A short overview of convex optimization

Energy Costs

number of cars (of type 1)
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Energy Costs

number of cars (of type 1)
A short overview of convex optimization

Energy Costs

Solution point (in 1D)

number of cars (of type 1)
Results
Three results

1) Emissions & Air quality management
2) Public health & planning
3) Energy policy
The Luxembourg Country:

- **Scenario 1**: NO\textsubscript{x} national emissions.
- Uncertainty of the air quality model, using 95% of the upper limit of the confidence interval.

![Graphs](image-url)
Results - e.g. Luxembourg (Scenario 2)

The Luxembourg Country:

Scenario 2: NO$_x$ sectoral emissions.

- Expected AOT$_1$
- Upper AOT$_1$

- Transport
- Residential
- Others

Air Quality Threshold (µg m$^{-3}$): 40, 45, 50, 55, 60, 65, 70, 75, 80

NO$_x$ emissions [t]
Results - e.g. Luxembourg region

The Luxembourg Region:

- NO\textsubscript{x} national emissions.

\begin{align*}
\text{Daily average} \\
\text{AOT}_{40}
\end{align*}
Thank you


Zachary D.S. and Dobsen, S. Does urban space evolve deterministically or entropically? An exploration of urban development models for Sheffield, UK in relation to decentralized energy policies, Energy Policy (In review), 2013


www.tudor.lu
2) Public health and planning

\[
\text{Min}\{\gamma(\varepsilon) \cdot I(\rho) : \rho(\varepsilon) - \rho \leq 0 \}
\]

\(\varepsilon\) = emission (tons per year) (decision variable)
\(\gamma\) = total discounted energy costs
\(I\) = impact function (ozone - health)
\(\rho\) = ozone concentration (ppb)
\(\rho\) = average ozone concentration (ppb) (decision variable)

With Impact considerations

Without Impact considerations