Applied Optimization in R – Energy Markets and Policy

Presentation to Bay Area R User Group

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May 7, 2019

Agenda

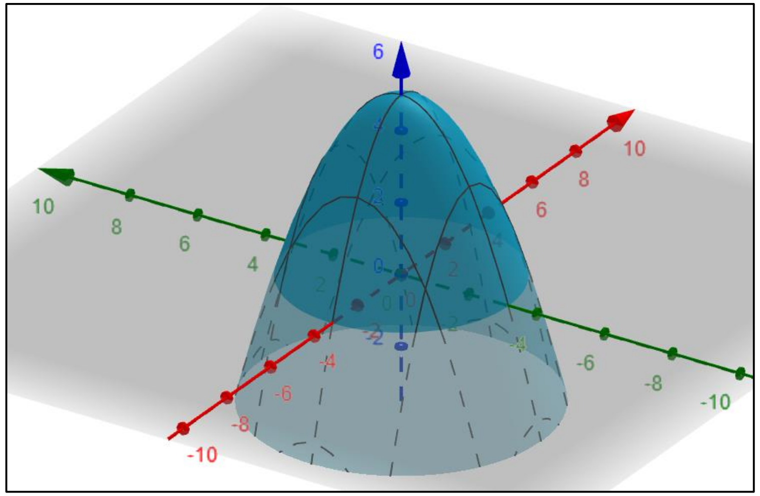
1. Background - mathematical optimization, linear programming (LP), and *LP Solve* package.
    - ~8 minutes

2. Application – energy markets and policy research.
    - ~12 minutes
    - Working paper: *Short run effects of carbon policy on U.S. electricity markets.* https://osf.io/preprints/socarxiv/b79yu/
    - Model data, code, and detailed results: https://osf.io/59pf6/

Mathematical optimization, an economic perspective

Economic actors often act as if they are maximizing or minimizing a function subject to constraints:

- Producers sell things to maximize profits subject to production constraints.
- Consumers purchase things to maximize utility, or happiness, subject to a budget constraint.
- Efficient markets help minimize costs.



Understanding market structure is fundamental to building a useful economic model:

- Degree of competition and market consolidation.
- Supply and demand characteristics.
- Time frame.

Linear optimization (Linear programming, LP)

Recipe for a linear optimization model:

$$\begin{aligned}
&\textit{choose } x\textit{'s to maximize or minimize}: \\
&c_1x_1 + c_2x_2 + \cdots + c_nx_n \\
\\
&\textit{subject to}: \\
&a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \leq b_1 \\
&a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n \leq b_2 \\
&\qquad\qquad\qquad \vdots \\
&a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n \leq b_m
\end{aligned}$$

$\Rightarrow$

$$\max_x \begin{bmatrix} c_1 & c_2 & \ldots & c_n \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$

$$\textit{subject to}:$$

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \leq \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix}$$

$\Downarrow$

$$\max_x \boldsymbol{c}^T \boldsymbol{x}$$

$$\textit{subject to } \boldsymbol{A}\boldsymbol{x} \leq \boldsymbol{b}$$

LP_solve

Open-sourced linear program solver written in C. http://lpsolve.sourceforge.net/5.5/

R package "lpSolve" provides interface. https://cran.r-project.org/web/packages/lpSolve/

```
lp(direction, objective.in, const.mat, const.dir, const.rhs, int.vec, binary.vec,…)
```

`direction`	"min" or "max"
`objective.in`	Vector of objective function coefficients ($\boldsymbol{c}$)
`const.mat`	Coefficient constraint matrix ($\boldsymbol{A}$)
`const.dir`	Vector of constraint directions ("$\leq$," "$\geq$"," "$==$")
`const.rhs`	Vector of values for right side of constraints ($\boldsymbol{b}$)
`int.vec`	index of integer-constrained variables
`binary.vec`	index of binary-constrained variables

$$\max\ \boldsymbol{c}^T\boldsymbol{x}$$

$$\text{subject to } \boldsymbol{A}\boldsymbol{x} \leq \boldsymbol{b}$$

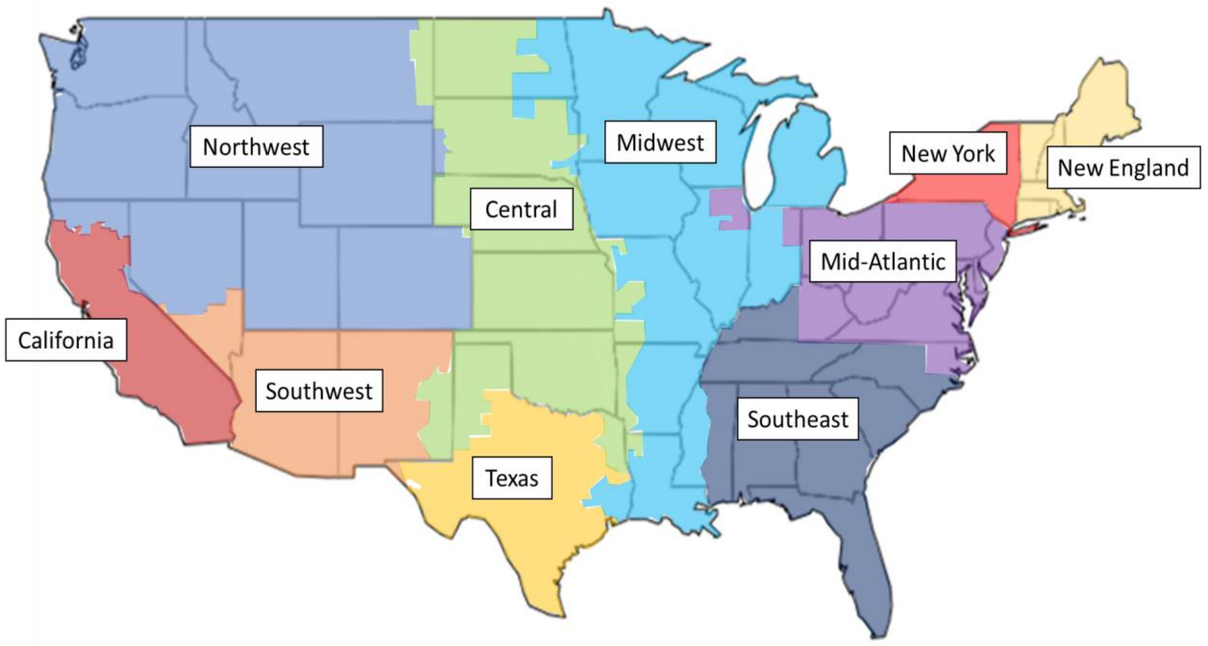
Application – Carbon policy and electricity markets

- Three national carbon price proposals were recently introduced in the U.S. congress (Kaufman, 2018).
- I built an LP model of the U.S. electricity market and simulated short run effects of \$25/ton and \$50/ton carbon prices.
- Conclusions:
  - Carbon price induces significant short term greenhouse gas emissions reductions by switching electricity production from coal to natural gas.
  - Prices of \$25 and \$50 reduce emissions 17% and 22% from today's baseline, respectively.
  - State-level insights: 1) A flat per capita rebate leads to wealth transfer across states, and 2) the modeled cost-minimizing policy response includes increased emissions in 15 states, due to increased natural gas consumption.

Model overview (1)

- Separates the U.S. electricity system into 10 market regions.

- Minimize system production costs, subject to:
    - Hourly regional supply = Hourly regional demand.
    - Regional transmission constraints
    - Plant-level capacity constraints



Model overview (2) Algebra

The optimization problem is formulated as follows:

$$(1)\ \underset{q_{r,p,t},\ qtx_{r',r,t}}{\text{minimize}} \sum_{r}\sum_{p\in r}\sum_{t} q_{r,p,t}(c_{p,t} + CO_{2p}fee_r)\,, \forall\, t$$

(1) Minimize system costs by choosing hourly generation and transmission levels.

Subject to the following sets of constraints:

Subject to:

$$(2)\ \sum_{p\in r} q_{p\in r,t} + \sum_{r'\neq r}(qtx_{r',r,t} - qtx_{r,r',t}) + imp_{r,m} \geq D_{r,t} + O_{r,t},\quad \forall\, r,m,t \in m$$

(2) Supply equals demand.

$$(3)\ 0 \leq q_{p,t} \leq Q_{p,m},\quad \forall p,m,t \in m$$

(3) Plant capacity constraints.

$$(4)\ -tx_{r',r} \leq qtx_{r',r,t} \leq tx_{r',r}, \forall\, r, r' \neq r, t$$

(4) Regional transmission constraints.

The objective function in equation (1) minimizes production costs, including the carbon price. Equation (2) requires that production plus net imports from all other regions meets demand plus operating reserves in region r, for all hours. Equations (3) limits production from each plant to be less than or equal to its total capacity and non-negative. Equation (5) limits energy transfers across market regions to the available transmission capacity available between each pair of market regions.

Model overview (3) – Data objects

$$\max_{x} \boldsymbol{c}^T \boldsymbol{x}$$

$$subject\ to\ \boldsymbol{Ax} \leq \boldsymbol{b}$$

$\boldsymbol{x} \in \mathbb{R}_+^n$ vector of power plant production decisions ($\boldsymbol{q}$) and transmission levels ($\boldsymbol{qtx}$).

$\boldsymbol{c} \in \mathbb{R}_+^n$ vector of power plant production costs and transmission costs.

$\boldsymbol{b} \in \mathbb{R}_+^m$ vector of power plant and transmission capacity constraints, and regional demand constraints.

$\boldsymbol{A} \in \mathbb{R}_+^{m \times n}$ constraint coefficients

$$\begin{array}{r c} & \begin{array}{cc} P & TX \end{array} \\ \begin{array}{r} P\text{ plant capacity constraints} \\ TX\text{ transmission capacity constraints} \\ R\text{ demand constraints} \end{array} & \left(\begin{array}{c:c} \boldsymbol{I} & \boldsymbol{0} \\ \hdashline \boldsymbol{0} & \boldsymbol{I} \\ \hdashline \boldsymbol{D} & \boldsymbol{T} \end{array}\right) = \boldsymbol{A} \end{array}$$

<u>Dimensions:</u>

P 8,377 power plants

TX 90 transmission constraints

R 10 market regions

$n = P + TX = 8{,}467$

$m = P + TX + R = 8{,}477$

<u>Definition of R demand constraints:</u>

$$d_{r,p} = \begin{cases} 1 & if\ p \in r \\ 0 & otherwise \end{cases}$$

$$t_{r,tx} = \begin{cases} 1 & if\ tx \in r \\ 0 & otherwise \end{cases}$$

Model overview (4) – Stylized R code

```
lp(direction, objective.in, const.mat, const.dir, const.rhs, …)
```

```r
library(lpSolve)

### Model dimensions ###
P <- 8377; TX <- 90; R <- 10

### Create coefficient constraint matrix ###
# Plant capacity constraints:
A <- cbind( diag(P), matrix(0, nrow=P, ncol=TX) )
# Transmission capacity constraints:
tx_coef <- cbind( matrix(0, nrow=TX, ncol=P), diag(TX) )
A <- rbind(A, tx_coef)
# Demand constraints
dem <- c(d, t)
A <- rbind(A, dem)

### Assign remaining inputs ###
# Objective function coefficients
c <- c(costs, rep(0, TX))
# Constraint values
b <- c(plant_cap, tx_cap, demand)
# Constraint direction
direction <- c(rep('<=', P + TX), rep('>=', R))

### Solve the model ###
lp <- lp('min', c, A, direction, b)

### Access results ###
x <- lp$solution
prices <- lp$duals

```

$$\max_{x} \mathbf{c}^T \boldsymbol{x}$$

$$\textit{subject to } \boldsymbol{A}\boldsymbol{x} \leq \boldsymbol{b}$$

$$\begin{array}{r c} & \begin{array}{cc} P & TX \end{array} \\ \begin{array}{r} P \text{ plant capacity constraints} \\ TX \text{ transmission capacity constraints} \\ R \text{ demand constraints} \end{array} & \left(\begin{array}{c:c} \boldsymbol{I} & \boldsymbol{0} \\ \hdashline \boldsymbol{0} & \boldsymbol{I} \\ \hdashline \boldsymbol{D} & \boldsymbol{T} \end{array}\right) = \boldsymbol{A} \end{array}$$

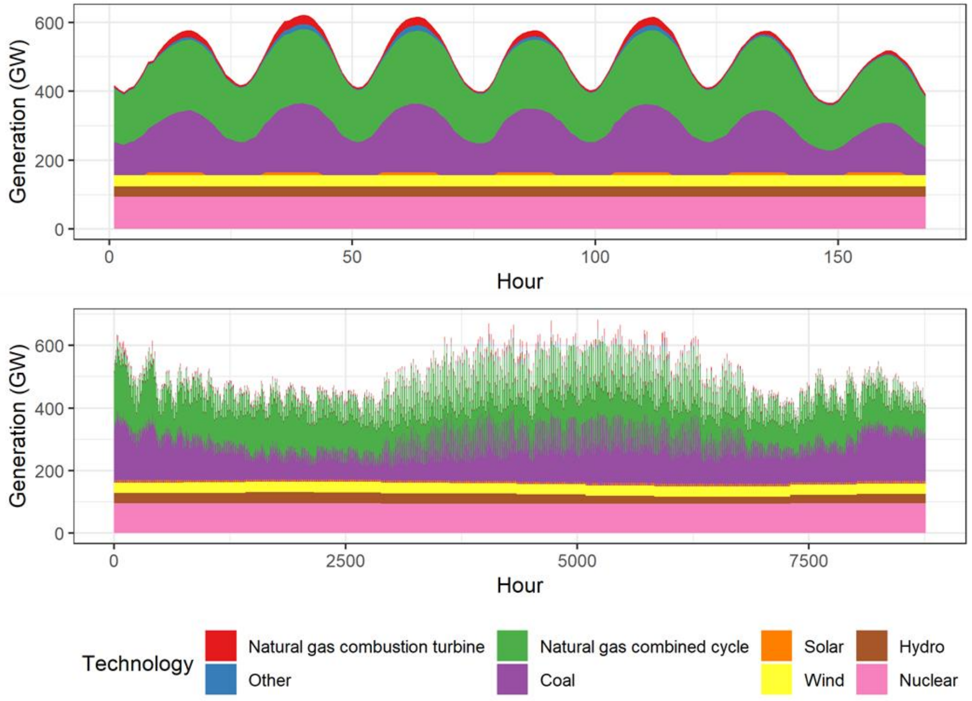
Full analysis available online: https://osf.io/t48w3/

- Scripts 1:29 download and clean data
- Scripts 30:33 solve the model
- Scripts 34:46 analyze results

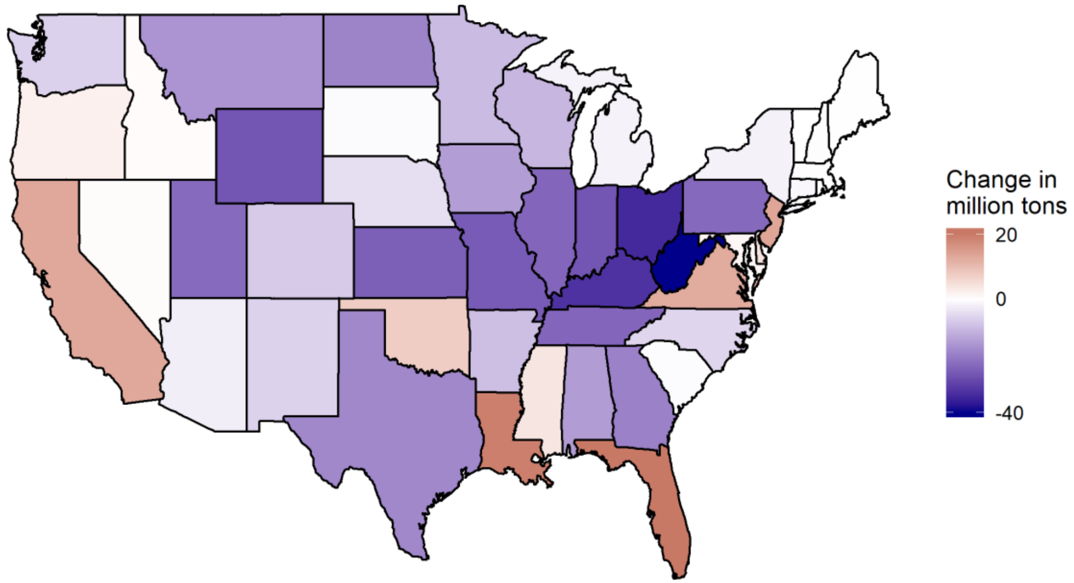
Model output

Electricity generation, prices, and greenhouse gas emissions.

Modeled U.S. electricity production for first week of July (top) and one year (bottom):



Change in CO_2e emissions by state after $50/ton tax:



Conclusions

- *Lp_solve* is an open-sourced linear optimization solver that can be accessed in R with the *lpSolve* package.
- An application for energy economics and policy was presented.
- A model of the U.S. electricity market was built and the effects of greenhouse gas emissions policy were simulated.

References

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Appendix – Model Parameters

The model includes the following parameters:

$Q_{p,m}$	maximum operating capacity of plant p during month m in megawatts (MW)
$c_{p,t}$	production cost of plant p in hour t, in dollars per megawatt-hour ($\$/MWh$)
CO_{2p}	carbon dioxide emissions rate for plant p, in $\frac{tons\ CO_2}{MWh}$
$D_{r,t}$	demand in market region r during hour t, in MWh
$O_{r,t}$	hourly operating reserves in region r, in MWh
$tx_{r',r}$	transmission capacity from region r' to region r, measured in MWh
$imp_{r,m}$	average net international imports into market region r for month m
fee	carbon price imposed by policy, in $\$/MWh$

The set of choice variables are the level of production from each plant for each hour, $q_{p,t}$, and the levels of power transferred between each region, $qtx_{r',r,t}$. The model assumes operators for each market regio coordinate to minimize the cost of dispatching power plants subject to demand levels.

Appendix – Data

- Power plant characteristics, electricity demand, transmission flows from the U.S. Energy Information Administration.
- Electricity production costs from the National Renewable Energy Laboratory.
- Greenhouse gas emissions data from the U.S. Environmental Protection Agency.
- Electricity outage data from the North American Electric Reliability Corporation.
- Baseline greenhouse gas costs from The World Bank carbon price dashboard.