Pathways to Deep Decarbonization: Large Scale Data and Models for Finding Them

Steven O. Kimbrough

Operations, Information and Decisions, and Philosophy Departments.
Slides at `https://github.com/stevenokimbrough/presentations/preceptorial-new-student-orientation-2019.pdf`

2019-08-24: Penn First Year Experience (FYE) Preceptorial, G65 JMHH 11:00–1:00

Pathways to Deep Decarbonization: Large Scale Data and Models for Finding Them

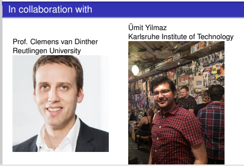
A description:
Any successful response to the climate crisis will require eliminating greenhouse gas emissions entirely or almost entirely from our electric power systems ("deep decarbonization"). In addition, these systems will need to be greatly expanded as the electrification of our economy, indeed society, proceeds. Relying on renewable energy resources for deep decarbonization is problematic because they are intermittent. They come and go uncontrollably, quite independently of our need to use electricity. In consequence, careful, detailed modeling and analysis is needed in order to find workable ways to decarbonize the electricity grid. The problem is very complex and (likely) does not admit of any simple solution.
This class is a tutorial introduction, suitable for incoming freshmen, to the problem of finding pathways to deep decarbonization. We will focus on characterizing the problem and its difficulty, on surveying how large scale data and modeling are being applied to the problem, and on what these studies are telling us. The course will alternate between short lectures that present the material and interactive sessions in which participants will explore policy and social implications of the findings presented.

G65 JMHH 11:00–1:00

In collaboration with

Prof. Clemens van Dinther
Reutlingen University

Ümit Yilmaz
Karlsruhe Institute of Technology



Ümit is photographed at Tattooed Mom in Philadelphia, spring 2019. https://www.tattooedmomphilly.com/, 505 South Street.

Outline

In a nutshell

This whole presentation is a speed drill. Here is a speed dill on a speed drill.

1. We investigate how deep decarbonization of the electricity system can be be achieved.
2. Why? Climate crisis.
3. Focus: The European union.
4. We build a large scale optimization model for planning electricity generation through 2050.
5. We find that neither business as usual nor a carbon price of 160 €/ton of CO2 emitted is sufficient for deep decarbonization by 2050.
6. Power to gas can save us.

Now, details of the story.

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We use the term *carbon price* to cover any fee assessed for carbon emissions, whether by a carbon tax, a cap and trade program or some other measure.

Goals for the Session

(a) Aimed at incoming freshmen; non-experts
A minimally technical session

(b) Discuss climate change, specifically mitigation

(c) Discuss modeling

(d) Discuss data

(e) Discuss modern decision making and “thinking with models”

(f) Aim to teach and to intrigue, to pique your curiosity

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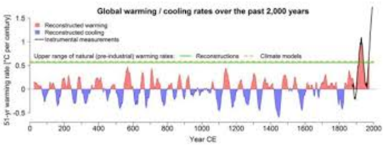
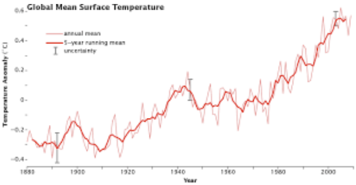
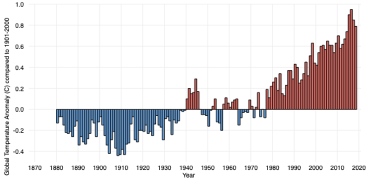
A shoutout to data, big data. The theme of the year at Penn. The message here is rather different than that in *Weapons of Math Destruction.* Modern decision making often requires big modeling and big data. Today we will see an example, preceded by necessary setup.

Climate Change

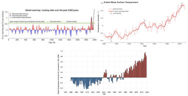






1. Contested term
   See [Atanasova and Fløttum, 2019]
2. Regardless of terminology, global warming is real, is here, and is dangerous. A very serious problem. [NOAA, 2019]

Climate Change



1. Contested term
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Alternatives to “climate change” include: global warming, global heating, climate crisis, climate emergency. It’s in flux. The term comes from Frank Luntz a Penn graduate and prominent Republication operative. He also of “death tax” instead of “inheritance tax.”Clockwise from top left:

1. BBC 2000 years of temperature changes
2. NASA
3. NOAA and www.climate.gov

And the main cause is . . .

- Emissions/releases of greenhouse gas (GHG) Principally CO2, but also methane (CH4) and other substances
- Mostly due to human activities: burning fossil fuels
- Understood since the late 19th century. Subject of scientific consensus today and for some time. Exxon in the 1970s.
- As the earth warms, positive feedback due to release of frozen methane and changes in reflectance.

Nature of the problem

- "A stock problem, not a flow problem."
- CO_2 leaves the atmosphere too slowly to be significant on a human scale.
  $\approx$ Once it's in the air it stays there unless we remove it.
- We must see to it that the level of atmospheric CO_2 does not get too high.
  Could have runaway heating.
- Even so, a growing recognition that even when flows stop, it will be necessary to remove CO_2 from the atmosphere.
  Expensive!

What to do?

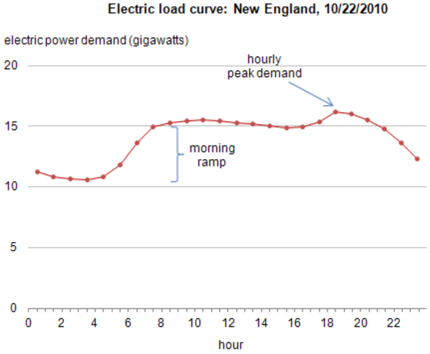
1. Mitigation
   Reduce GHG emissions. Remove GHG from the air.
2. Adaptation
   Getting along in the new environment.
3. Transition
   How do we get there from here?
   How do we build a fair and flourishing society?

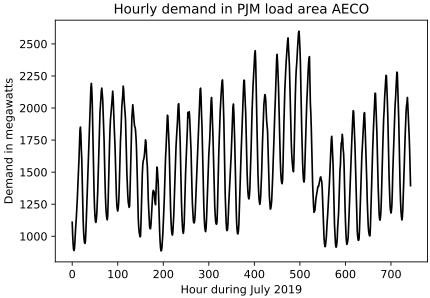
Our focus now: mitigation and transition in the electric power system. In the US about $\frac{1}{3}$ of the GHG emissions are due to electric power generation.
Going forward, we need to “electrify everything” and eliminate GHG emissions from electric power generation.
How can we transition to green electricity?

Figure it out with modeling

But there are fundamental challenges to be addressed

- Demand for electricity varies during the day, by day, by time of year, by year





https://www.eia.gov/todayinenergy/detail.php?id=830

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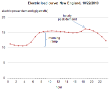

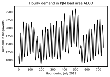

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http://dataminer2.pjm.com/list

Figure it out with modeling

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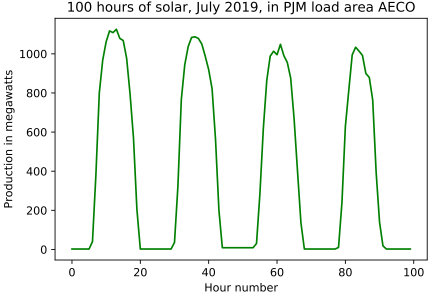
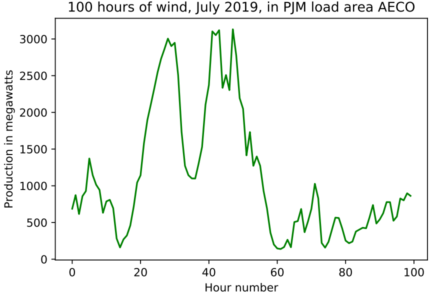
- Production of electricity by renewable generation varies during the day, by day, by time of year, by year





- And you can't dispatch renewables (much).

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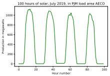

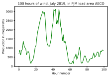

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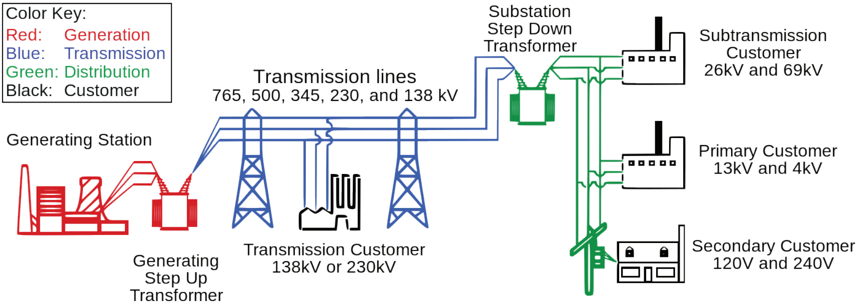
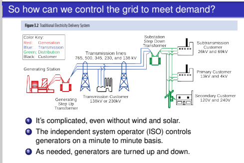
So how can we control the grid to meet demand?

Figure 3.2 Traditional Electricity Delivery System



1. It's complicated, even without wind and solar.
2. The independent system operator (ISO) controls generators on a minute to minute basis.
3. As needed, generators are turned up and down.



1. https://www.energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter3.pdf.
2. Be sure to make clear that the fine tuning, the “load following”, is very much subject to constraints.

Brute Facts: Lots of Dynamic Balancing Required

At scales ranging from minutes to years.
Only a few ways:

1. Flexible generation
   Gas generators, hydroelectric.
2. Storage
   Batteries, pumped hydroelectric storage, compressed air, gravity, etc.
3. Demand response
4. Transmission from distant sources
   6 p.m. Philadelphia is 3 p.m. Santa Barbara.

All of these are in use today. But VRE makes the problem worse and all of the ways are very expensive.

Huge challenge

1. Traditional systems are terribly complex and must be managed 24/7/365 to keep supply and demand in balance
2. Balancing becomes much more difficult with variable renewable energy (VRE)
3. But it's being done!
4. The challenge is worse as the percentage of VRE increases.
5. After 80% must rely on storage/backup in some form. You can't do 100% renewables!
6. Challenge: Find economical configurations that eliminate GHG emissions.
7. Put otherwise: Find economic paths to deep decarbonization of the electric power system. Start now (with existing plants) and plan to 2050.

Constrained optimization

1. We conceive of our problem as one of constrained optimization.
2. Optimization: maximize or minimize a function, called the objective function.
   Our objective function: represents the cost of building and operating an electric power grid.
   We want to minimize the cost.
3. But to be realistic we need to recognize constraints.
   Forecasted demand must be met. There must always be sufficient production.
4. Conceptually, that's the core:
   We represent our problem mathematically as an objective function to be minimized, subject to (while) making sure none of the constraints are violated.

Optimal solution: a profound concept

- With wide ramifications, FYI. Proceed simply here.
- Idea: A best compromise solution to a problem; the best we can do under the circumstances.
- Can make this precise with mathematical presentations.
- Decision variables: under our control. Objective function: to be optimized by setting (choosing values for) the decision variables. Constraints: represent real world facts, limit our freedom of action.
- Optimal solution: a setting of the decision variables in which the constraints are satisfied, and there is no better setting (wrt objective function) that also meets the constraints.

Linear programming problems

$$\text{Maximize} \quad z = \sum_{j \in J} c_j x_j \tag{1}$$

Subject to:

$$\sum_{j \in J} a_{ij} x_j \leq b_i, \quad \forall i \in I \tag{2}$$

$$x_j \geq 0, \quad \forall j \in J \tag{3}$$

Figure: A canonical schema for linear programming models.

From [Kimbrough and Lau, 2016, Chapter 2].

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To optimize: find a setting of the decision variables that minimizes the objective function and satisfies the constraints.

1. Decision variables: x_js.
2. Parameters or data: c_js, a_{ij}s.
3. Objective function. Constraints.
4. Notice the set notation J and I are sets. This is a schema that fits arbitrarily large problems.

Simple example: linear programming problem

From [Kimbrough and Lau, 2016, Chapter 3].

$$\text{Minimize} \quad z = 41x_1 + 35x_2 + 96x_3 \tag{4}$$

Subject to:

$$2x_1 + 3x_2 + 7x_3 \geq 1250 \tag{5}$$

$$1x_1 + 1x_2 + 0x_3 \geq 250 \tag{6}$$

$$5x_1 + 3x_2 + 0x_3 \geq 900 \tag{7}$$

$$0.6x_1 + 0.25x_2 + 1x_3 \geq 232.5 \tag{8}$$

$$x_1 \geq 0, x_2 \geq 0, x_3 \geq 0 \tag{9}$$

Figure: Wagner Diet linear programming model [Wagner, 1969].

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Figure: Wagner Diet linear programming model [Wagner, 1969].

parameters: 13

How do we solve these things?

1. You can't use calculus.
   Calculus lets you optimize a single function, but can't handle constraints. Other methods are needed.
2. Instead we use *mathematical programming solvers*.
   Computer software that implements general procedures people have discovered for solving the problems.
3. In the case of linear programming, modern commercial solvers can efficiently solve problems with millions of decision variables and many thousands of constraints.
   Our model is a case in point, although computational cost is an issue.

Basic workflow

1. Conceptualize the model mathematically
2. Translate the mathematical representation to an appropriate solver (computer optimization program) language, e.g., GAMS, MATLAB, Gurobi.
3. Collect data for the values of the constants (parameters) of the model, and arrange to connect it with the computerized representation.
4. Provide the solver with directions.
5. Have the solver execute its solution procedure.
6. Examine the output, including solution found, objective function value, various diagnostics.

And then the real work begins, the work of *post-solution analysis* [Kimbrough and Lau, 2016]. (But that's for another time.)

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GAMS, MATLAB. `https://www.gams.com/` Gurobi `https://www.gurobi.com/` good for examples: `https://www.gurobi.com/resources/food-manufacture-i/`
MATLAB `https://www.mathworks.com/` support `https://www.mathworks.com/support.html?s_tid=gn_supp`
example `https://www.mathworks.com/help/optim/ug/example-linear-programming.html`
`https://www.mathworks.com/videos/mathematical-modeling-with-optimization-part-2a-problem-`
`html` `https://www.mathworks.com/videos/mathematical-modeling-with-optimization-part-2-68974.html`

PERSEUS-EU

1. Extends and modifies a general framework.
2. Model period: 2015–2050. 28 countries (EU28 without the islands of Cyprus and Malta but including Switzerland and Norway). Linear programming, implemented in GAMS. Each country represents a node with power transmission between neighbors. Time: by hour. (Note: 8,760 hours in a normal year, $30 \times 8760 = 262,800$ (so we sample))

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In our current model we use 4 weeks each year (by season) 2015–2050.

Decision variables

(Types of electricity production in the base case: coal, lignite, gas, nuclear, wind, solar PV, hydroelectric, biomass, pumped storage)

1. Productive capacity for different types of generation, by time and country
2. Investment in new production capacity, by type, time, and country
3. Energy flows between neighboring countries
4. In all, with time sampling, 11,663,070 decision variables in the model for the results presented here.

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The main decision variables of the optimization model are the production level of existing capacities, investment in new capacities and energy exchange flows between neighboring market areas. In addition to future capacity and production mix, the results deliver among others details on primary energy mix, cross border exchanges, emissions in each country and marginal costs of electricity generation. We have every single existing conventional power plant in 2015 in Europe. (We bought them from the following source: Platts. World electric power plants database, 2015 `https://www.spglobal.com/platts/en/products-services/electric-power/world-electric-power-plants-database`) Renewable technologies are aggregated. Capacities available in 2015 come from different sources, as no single source was completely correct. If you want to refer to a source, you can use the following source: EU Reference Scenario 2016 - Energy, transport and GHG emissions Trends to 2050.

Data

(Constants in the model number 4,980,247.)

1. Hourly (forecast) demand by country.
2. Forecast prices for equipment, fuels, operating costs
3. Assumptions about economic lives of various kinds of production
4. Pertaining to constraints, e.g., nuclear phase out in Germany, system balance
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LP has 4980247 rows (constraints), 11663070 columns (variables), and 41037460 nonzeros. The information on this slide are correct. I think you're asking me about the sources. They are already in the paper. You can find them in chapter 6.4 of our paper. Hourly (forecast) demand by country. It is not a forecast. It is 2015 demand data: ENTSOE, https://www.entsoe.eu/ Hourly weather dependence of the RES is also from 2015 data of the same source. Increase in the demand over the years: : EU Reference Scenario 2016 - Energy, transport and GHG emissions Trends to 2050.

2 Forecast prices for equipment, fuels, operating costs Fuel: and CO2-Certificate prices International Energy Agency. World energy outlook 2016, 2016. Equipment, Operating Costs: Deutsches Institut für Wirtschaftsforschung (DIW). Current and prospective costs of electricity generation until 2050,2013.

3 Assumptions about economic lives of various kinds of Production Deutsches Institut für Wirtschaftsforschung (DIW). Current and prospective costs of electricity generation until 2050,2013.

4 Pertaining to constraints, e.g., coal phase out, nuclear phase out in Germany, system balance The phase-out of nuclear energy in Germany is included. However, the phasing out of coal is not a good example. It is not included in the model, as there is still no political decision.

PERSEUS Equations: Objective function

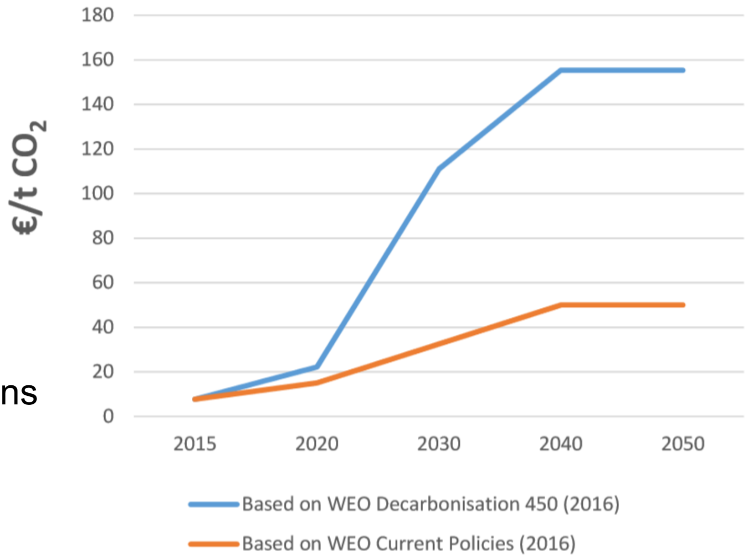
Uses set notation and so can represent indefinitely large models (time periods, generator types, etc.) The constraints add further complexity.

$$min \sum_{y \in Y} \left(\frac{1}{1+r}\right)^{y} \cdot \left(\begin{array}{l} \sum_{so \in SO} \sum_{no \in NO} \sum_{ec \in EC} FL_{so,no,ec,y} \cdot c^{fuel}_{so,no,ec,y} \\ + \sum_{u \in U} (K_{u,y} \cdot c^{fix}_{u,y} + K^{new}_{u,y} \cdot c^{inv}_{u,y}) \\ + \sum_{pc \in PC} \left(\begin{array}{l} PL_{pc,y} \cdot c^{var}_{pc,y} \\ + \sum_{t \in T} \left(\begin{array}{l} LV^{up}_{pc,y,t-1,t} \\ + LV^{down}_{pc,y,t-1,t} \end{array} \right) \cdot c^{lv}_{pc} \end{array} \right) \end{array} \right)$$

Scenarios

1. Necessary, because of complexity
2. For now: base case, base case plus higher carbon price, higher carbon price and P2G, plus batteries.

Base Case versus Base Case with High CO2 Prices



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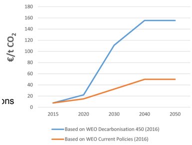
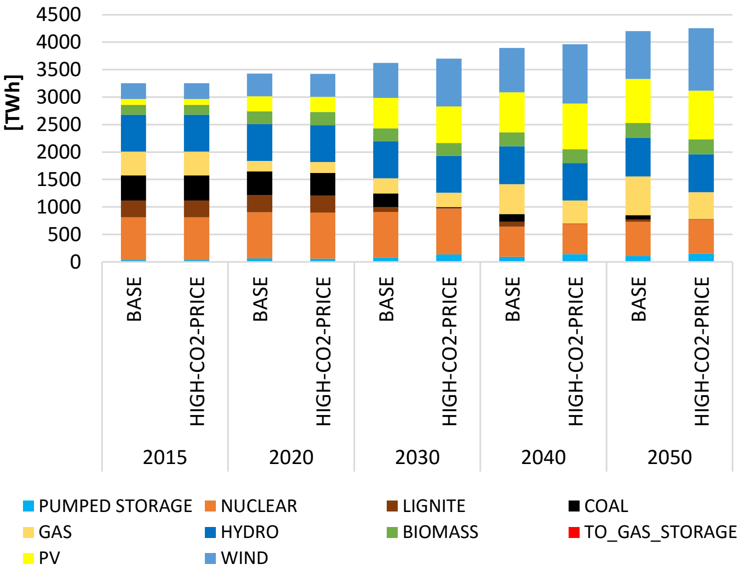
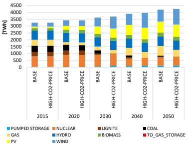


1. High versus Low CO2 Prices
2. WEO = World Energy Outlook, which is from the IEA, International Energy Agency.

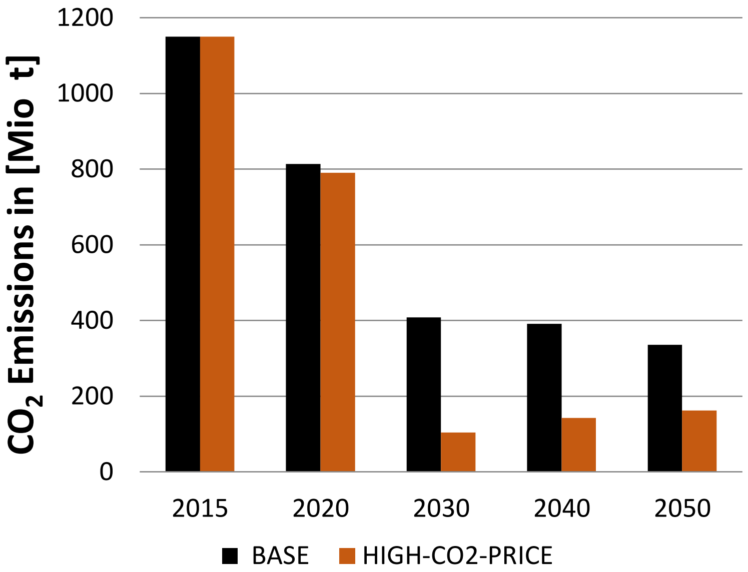
Base Case versus Base Case with High CO2 Prices

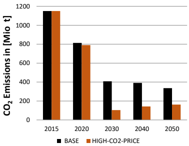




Production Mix. In both scenarios, electricity generation from renewable energies increases due to cost reductions in renewable energies.

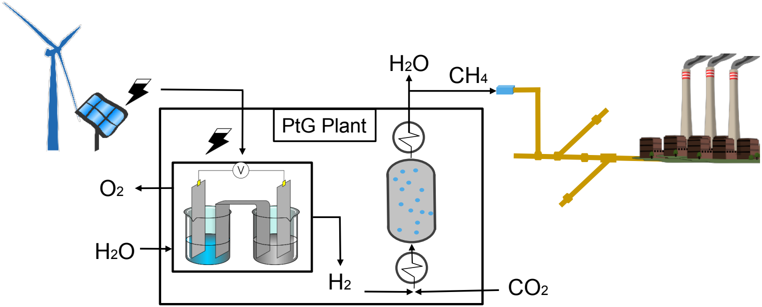
Base Case versus Base Case with High CO2 Prices





Emissions. Emissions are significantly lower in HIGH-CO2-PREIS due to high CO2 Certificate assumptions.

Real progress, but emissions are still far too high.



1. Power to Gas (PtG). Here, excess renewable electricity to create H2, then convert H2 to methane.
2. Key is to over configure the grid with renewable generation then use the excess for PtG.
3. What's optimal? Will it work?

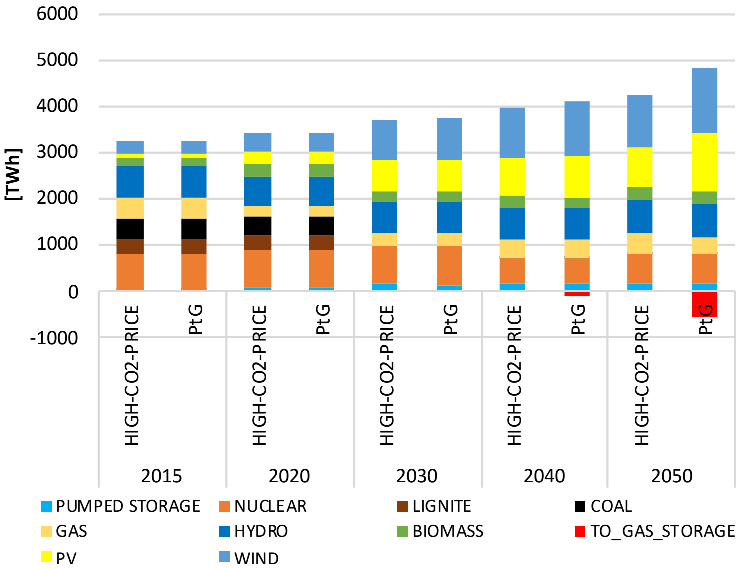
Table: Price assumptions for PtG plants

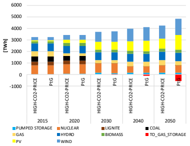
EURO\KW	2015	2020		2030		2040		2050	
		Low	High	Low	High	Low	High	Low	High
Invest	2000	1000	1300	700	900	575	800	450	700
Fix O&M*	40	20	26	14	18	11.5	16	9	14
Life Time	15	20		25		25		25	
Efficiency	0.6	0.616		0.68		0.714		0.756	

* 2% of the investment expenditures

1. We use the optimistic (low) investment cost estimates in these scenarios.

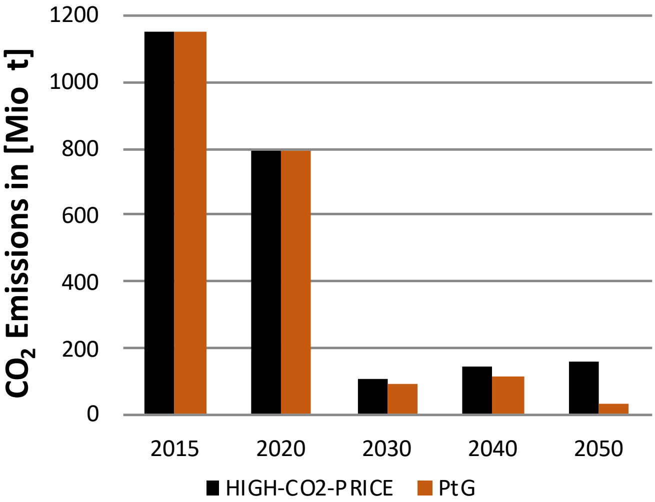
Base Case + High CO2 Price versus PtG + High CO2 Price





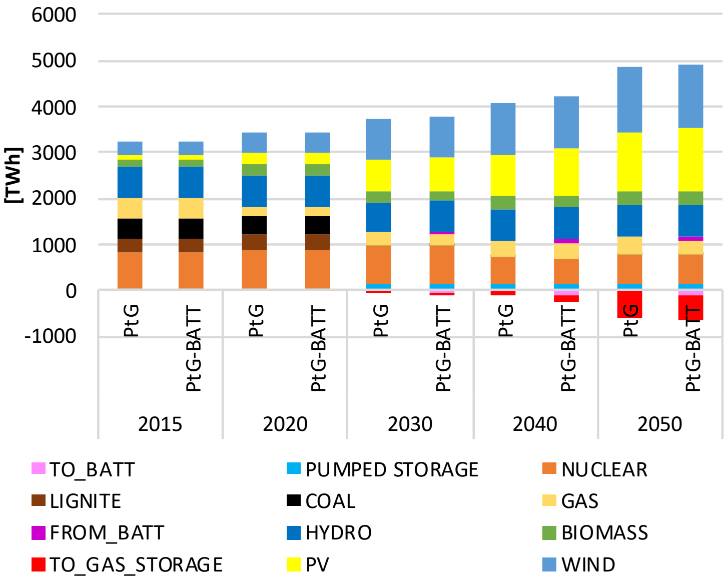
Generation. Comparing Base case with High CO2 price versus Base case with High CO2 price and PtG. Notice that solar PV is upped a lot, especially in 2050. Coal is priced out of the mixture by about 2030. PtG only comes in in 2030.(old) Slide 41: In the production mix diagram, the amount of electricity consumed for PtG is deducted from wind production. However, we have decided not to show it this way. You can find the corrected diagram on page 11 of the power point file.

Base Case + High CO2 Price versus PtG + High CO2 Price

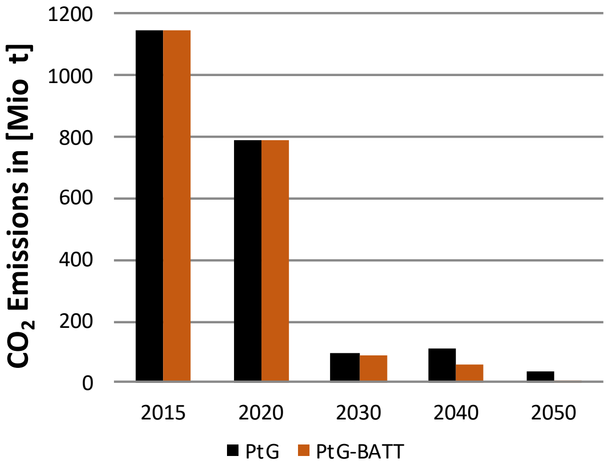


- PtG has a significant positive effect on emissions.

High CO2 Price: PtG versus PtG + Battery Storage



High CO2 Price: PtG versus PtG + Battery Storage



1. Emissions in the PtG-BATT scenario amount to about 8 million tons in 2050. Invisible on the graph.

Upshot

1. A carbon price of 160 €/ton is not sufficient for deep decarbonization by 2050.
2. How economically disruptive is a carbon price of 160 €/ton? Roughly, one US gallon of gasoline emits 20 pounds of CO2 when burned. 20 pounds is roughly 1% of a ton (metric, American, English). So, about 1.60 €/gallon of US gasoline. Not too bad.
3. A carbon price of 160 €/ton ($\approx$ \$160/ton), plus battery storage and PtG in the mix, is very close to sufficient for deep decarbonization (in the EU) by 2050 and is cheaper than the base case at the same carbon price.
4. No cause for despair on technical grounds. It comes down to politics and economic interests of fossil fuel owners.
5. **Make it cheaper!**

Thank-you for your attention

- Questions? Comments?
- Slides at `https://github.com/stevenokimbrough/presentations/preceptorial-new-student-orientation-2019.pdf`

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