Should we extract the European shale gas?
The effect of climate and financial constraints

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Introduction

- In France, the Jacob law of July 13th, 2011 bans hydraulic fracturing ("fracking"):
  "*Under the Environment Charter of 2004 and the principle of preventive and corrective action under Article L. 110-1 of the Environment Code, exploration and exploitation of hydrocarbon liquids or gas by drilling followed by hydraulic fracturing of the rock are prohibited on the national territory.*"
- Exploration licences held by companies like the American Schuepbach or the French Total cancelled.
- Schuepbach complains to the court that this law is unfair and unconstitutional
- The Constitutional Court confirms the ban on October 8th, 2013.
- French President François Hollande says France will not allow exploration of shale gas as long as he is in office.

- This position is supported by a majority of the population:
    - IFOP survey, Sept. 13, 2012: 74% of the respondents are opposed to shale gas exploitation;
    - BVA survey, Oct. 2, 2014: 62%.
    - This is greater than the opposition to nuclear energy, which provides most of France's electricity.
- France and Bulgaria are the only European Union countries to ban shale gas.

Arguments in favor of the ban

1. Fracking is dangerous and environmentally damaging:
   - pollution of surface water (through disposal of fracturing fluids);
   - pollution of groundwater (through accidental leakage of fracking fluids from the pipe into potable aquifers);
   - seismic vibrations caused by the injection of water underground;
   - concerns over landscape (lot of wells).
2. Global warming: we should reduce drastically the use of fossil fuels, not find new ones. Postpones the transition to clean renewable energy.

Arguments against the ban

- Natural gas is less polluting than other fossil fuels (oil, and particularly coal). Good substitute for coal.
- IMF, 2014: "*Natural gas is the cleanest source of energy among other fossil fuels (petroleum products and coal) (...). The abundance of natural gas could thus provide a "bridge" between where we are now in terms of the global energy mix and a hopeful future that would chiefly involve renewable energy sources.*"

- Enormous contrast between the position held by France and the situation of the US.
- US is the first natural gas producer in the world.
- Shale gas has risen from 2% of domestic energy production a decade ago to nearly 40% today (IMF, 2014).
- It has profoundly modified the energy mix: shale gas is gradually replacing coal for electricity generation.
  - 1990: coal-fired power plants produced more than half of the total electricity supply, and natural gas-fired power plants 12%;
  - 2013: respectively 29% and 27% (EIA, 2014).
- For shale gas supporters, the US shale boom has allowed to create jobs, relocate some manufacturing activities, lower the vulnerability to oil shocks, and impact positively the external balance (IMF, 2014).

Motivation

- We explore whether climate policy justifies developing more shale gas.
- Environmental damages, both local and global, are taken into account.
- To address the question of a potential arbitrage between shale gas development and the transition to clean energy, we examine how the results are modified when we add the constraint that total energy expenditures must not be increased by climate policy.

The model (1)

- Hotelling-like model of electricity generation.
- Electricity initially produced by coal-fired power plants.
- Two other energy sources, shale gas and solar, may be developed and used in electricity generation.
- Coal is abundant but very polluting.
  - Pollution intensity: θ_d.
  - Marginal production cost: c_d.
- Shale gas is non-renewable, and also polluting but less than coal.
  - Pollution intensity: $\theta_e \leq \theta_d$ (Heath *et al.*, PNAS 2014).
  - Marginal production cost: $c_e < c_d$ (EIA 2014).
  - Marginal local damage: d.
  - Reserves X_e endogenous.
  - Exploration cost $E(X_e)$, with $E'(X_e) > 0$ and $E''(X_e) > 0$, as in Gaudet and Lasserre (JEEM 1988). Must be paid at date 0. Actual extraction may be postponed to a later date.

The model (2)

- Solar is abundant and clean.
  - Marginal production cost: $c_b > \max(c_e + d, c_d)$.
  - Fixed R&D cost: $CF(t)$, with $CF'(t) < 0$ (exogenous technical progress).
- The 3 resources are perfect substitutes in electricity generation.
- Combustion of coal and shale gas generates carbon emissions that accumulate in the atmosphere:

$$\dot{Z}(t) = \theta_e x_e(t) + \theta_d x_d(t)$$

  No natural decay.
- Climate policy: cap on the atmospheric carbon concentration $\overline{Z}$ (Chakravorty *et al.* JEDC 2006).

	reserves		resources	
	EJ	GtC	EJ	GtC
conventional oil	4 900 – 7 610	98 – 152	4 170 – 6150	83 – 123
unconventional oil	3 750 – 5 600	75 – 112	11 280 – 14 800	226 – 297
conventional gas	5 000 – 7 100	76 – 108	7 200 – 8 900	110 – 136
unconventional gas	20 100 – 67 100	307 – 1026	40 200 – 121 900	614 – 1 863
coal	17 300 – 21 000	446 – 542	291 000 – 435 000	7 510 – 11 230
total	51 050 – 108 410	1002 – 1940	353 850 – 586 750	8 543 – 13 649

Reserves are those quantities able to be recovered under existing economic and operating conditions; resources are those whose economic extraction is potentially feasible.

Table: Estimates of fossil reserves and resources, and their carbon content. Source: IPCC WG III AR 5, 2014, Chapter 7 Table 7.2

coal	shale	unconventional	conventional
980	470	460	450

Table: Median estimate of life cycle GHG emissions (g CO_2eq/kWh) from electricity generated using coal or different types of natural gas. Source: Heath *et al.*, 2014

	levelized capital cost	fixed O&M	variable O&M including fuel	transmission investment	total
conventional coal	60	4.2	30.3	1.2	95.6
natural gas-fired CC	14.3	1.7	49.1	1.2	66.3
solar PV	114.5	11.4	0	4.1	130
solar thermal	195	42.1	0	6.0	243

Table: US average levelized cost of electricity (2012 $/MWh). Source: EIA, 2014a

The social planner's program

SP chooses:

- extraction and production rates $x_d(t)$, $x_e(t)$, $x_b(t)$,
- amount of shale gas developed X_e,
- date T_b at which the investment in solar plants is made,

which maximize:

$$\begin{aligned}&\int_0^\infty e^{-\rho t}\left[u\left(x_d(t)+x_e(t)+x_b(t)\right)\right.\\&\left.-c_d x_d(t)-(c_e+d)x_e(t)-c_b x_b(t)\right]dt\\&-E(X_e)-CF(T_b)e^{-\rho T_b}\end{aligned}$$

under constraints:

$$\int_0^\infty x_e(t)dt \leq X_e, \quad X_e(0)=X_e \text{ given}$$

$$\int_0^\infty (\theta_d x_d(t)+\theta_e x_e(t))dt \leq \overline{Z}-Z_0, \quad Z(0)=Z_0 \text{ given}$$

$$x_d(t)\geq 0,\ x_e(t)\geq 0,\ x_b(t)\geq 0$$

Constrained optimal price path (1)

For X_e and T_b given:
FOC, with $\lambda(t)$ the scarcity rent associated to the stock of shale gas and $\mu(t)$ the carbon value:

$$\begin{aligned} u'(x_d(t)) &\leq c_d + \theta_d \mu(t) \\ u'(x_e(t)) &\leq c_e + d + \lambda(t) + \theta_e \mu(t) \\ u'(x_b(t)) &\leq c_b \end{aligned}$$

with equality when the energy is actually used, and

$$\begin{aligned} \dot{\lambda}(t) &= \rho\lambda(t) \\ \dot{\mu}(t) &= \rho\mu(t) \text{ before the ceiling} \end{aligned}$$

Constrained optimal price path (2)

- X_e exhausted.
- Ceiling reached at date T_b.
- Energy sources used successively – no phase of simultaneous use.
- R&D costs $CF(t)$ paid when solar starts to be used, i.e. at date T_b.
- $c_e < c_d$ by assumption, but $c_e + d \gtreqless c_d$, depending on the size of the marginal local damage d. Determines which fossil fuel is used first.

Constrained optimal price path (3)

Large local damage: $d > c_d - c_e$

Price path potentially composed of three phases:

1. Coal used between 0 and T_e;
2. shale gas used between T_e and T_b, with continuity of the energy price at date T_e;
3. solar used from T_b onwards.

One (or two) of these phases may not exist.

- Absent climate policy ($\overline{Z} \to \infty$), pollution does not matter $\Longrightarrow$ coal used alone forever.
- $\overline{Z}$ finite $\Longrightarrow$ switch to solar at some point. But is it useful to use shale gas as well?
  - If θ_e close to θ_d, shale gas never developed.
  - If θ_e close to zero and ceiling constraint very tight, shale gas may be exploited from the beginning and coal completely evicted.

Constrained optimal price path (4)

Small local damage: $d < c_d - c_e$

Again, price path potentially composed of 3 phases:

1. Shale gas used between 0 and T_d;
2. Coal used between T_d and T_b;
3. Solar used at price c_b from T_b onwards.

Solution (1)

X_e and T_b chosen optimally:

- X_e s.t.
$$\lambda_0 = E'(X_e)$$
- T_b s.t. marginal benefit of postponing the switch to solar $=$ marginal cost.
- The energy price jumps downwards at date T_b.

Solution (2)

Optimal succession of energy sources as a function of the stringency of climate policy

large local damage

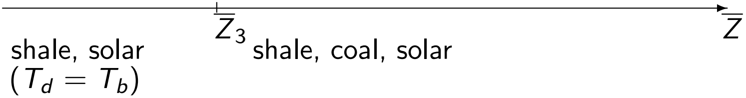
$\overline{Z}_2$ $\overline{Z}_1$ $\overline{Z}$

shale, solar
($T_e = 0$)

coal, shale, solar

coal, solar
(d high enough)

small local damage



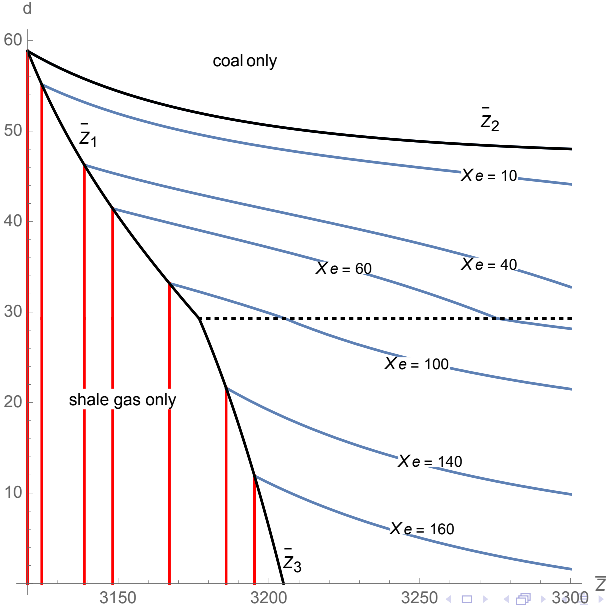
$\overline{Z}_3$ $\overline{Z}$

shale, solar
($T_d = T_b$)

shale, coal, solar

Solution (3)

The trade-off between local and global damages



Comparative dynamics (1)

Large local damage

$$\frac{\partial T_e}{\partial \overline{Z}} > 0, \qquad \frac{\partial T_b}{\partial \overline{Z}} > 0, \qquad \frac{\partial X_e}{\partial \overline{Z}} < 0$$

- Lenient climate policy: few (or no) shale gas developed. Energy mix before the ceiling mainly composed of coal.
- More stringent climate policy: use of shale gas more interesting because of its lower carbon content $\Longrightarrow$ it is optimal to use shale gas earlier and to develop it in a greater amount, and to use less coal.
- A more severe climate policy makes the switch to solar happen earlier.

Comparative dynamics (2)

Small local damage

$$\frac{\partial T_d}{\partial \overline{Z}} < 0, \qquad \frac{\partial T_b}{\partial \overline{Z}} > 0$$

- Remember that in this case shale gas is developed first.
- When climate policy becomes more stringent, the date of the switch to coal is postponed while the date of the switch to solar is brought forward.

$$\text{if } \theta_e = 0, \ \frac{\partial X_e}{\partial \overline{\overline{Z}}} < 0$$

$$\text{if } \theta_e = \theta_d, \ \frac{\partial X_e}{\partial \overline{\overline{Z}}} > 0$$

- When shale gas is not polluting, the more stringent climate policy is, the more shale gas is developed.
- When shale gas is as polluting as coal, the more stringent climate policy is, the less shale gas is developed. Shale gas is evicted by solar.
- If $\theta_e < \theta_d$ and if the price elasticity of demand is low, the more stringent climate policy is, the more shale gas is developed.

Constraint on energy expenditures (1)

Solution

- Present value of total energy expenditures:

$$\begin{aligned} A_0 = \int_0^{\infty} & e^{-\rho t} \left[c_d x_d(t) + c_e x_e(t) + c_b x_b(t) \right] dt \\ & + E(X_e) + CF(T_b) e^{-\rho T_b} \end{aligned}$$

- Constraint:

$$A_0 \leq A_0^{\mathrm{ref}}$$

  with A_0^{ref} the present value of energy expenditures absent climate policy.

- Reference absent climate policy:
  - large local damage: coal used alone;
  - small local damage: shale gas used first, then coal.
  - solar never developed.

- The constraint increases the monetary costs of energy generation (extraction, investment and O&M costs) compared to the non-monetary environmental cost (local damage d).
- $\Longrightarrow$ incentive to develop more shale gas and extract it earlier.
- But other effects can play in the opposite direction.
- In the realistic case of a low price elasticity of electricity demand, a binding financial constraint leads to developing more shale gas and postpones the switch to solar.

Calibration (1)

Functional forms:

$$\begin{aligned} u(x) &= ax - b\frac{x^2}{2} \Longrightarrow D(p) = \frac{a-p}{b} \\ CF(t) &= CF_0 e^{-\gamma t} \\ E(X_e) &= \frac{\varepsilon}{2} X_e^2 \end{aligned}$$

Calibration (2)

- Unit costs $c_d = 95.6\$/\text{MWh}$, $c_e = 66.3\$/\text{MWh}$ and $c_b = 130\$/\text{MWh}$ (US levelized cost of electricity from EIA, 2014a).
- Emission coefficients $\theta_d = 0.98$ tCO_2eq/kWh and $\theta_e = 0.47$ tCO_2eq/kWh.
- Rates of discounting and technical progress: $\rho = 0.02$ and $\gamma = 0.03$.
- Initial carbon concentration in the atmosphere: $Z_0 = 400$ ppm.
-
    - Around 50% of total emissions is projected to come from electricity generation.
    - Around 11% of GhG emissions come from the European Union.
    - $\Longrightarrow$ a 3°C target corresponds to a European sectoral ceiling in electricity generation of 408 ppm.

Calibration (3)

- The fixed cost of developing a clean technology at date 0, CF_0, is assumed to be the investment necessary to solve the intermittence problem (infrastructure and storage). It is calibrated using the French Environment and Energy Management Agency report (ADEME, 2015) : 329 Million €/year.
- Demand elasticity at 95.6\$/MWh = 0.25 (Alberini *et al.*, 2011).
- Marginal cost of shale gas exploration calibrated using data on US shale wells (EIA Natural Gas Weekly Update).

Simulations (1)

- Large marginal local damage: we take $d = 3/4 * c_e$.
  - It is then optimal to switch from coal to shale gas in $T_e = 30$ years, and from shale gas to solar in $T_b = 34$ years.
  - Very few shale gas is extracted (5.7% of total European resources are developed).
- Small marginal local damage: $d = 1/4 * c_e$. Then coal is completely evicted by shale gas.
- Small marginal local damage $d = 0.4 * c_e$ (to have an interior solution where the 3 energy sources are used):
  - it is then optimal to switch from shale gas to coal in $T_d = 60.7$ years, and from coal to solar in $T_b = 62.5$ years.
  - Now, very few coal is extracted. The quantity of shale gas developed is $X_e = 126.4\ 10^9$ MWh, i.e. 92% of the total recoverable resources.

Simulations (2)

The consequences of a financial constraint

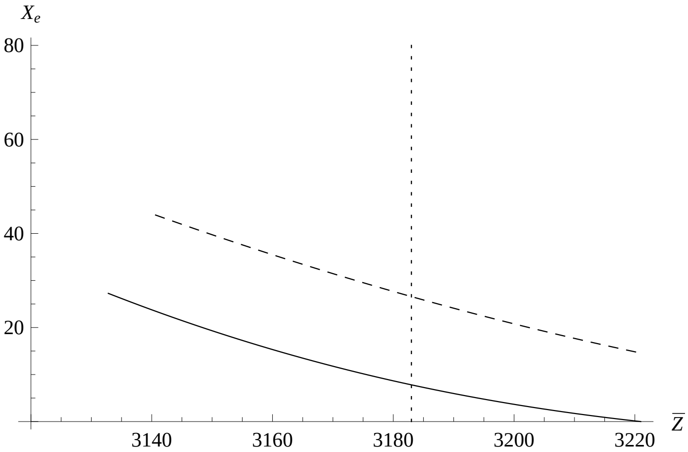


Figure: Quantity of shale gas developed as a function of the value of the ceiling in the reference case (solid line) and the constrained case (dotted line) when the marginal local damage is large

Simulations (3)

The consequences of a financial constraint

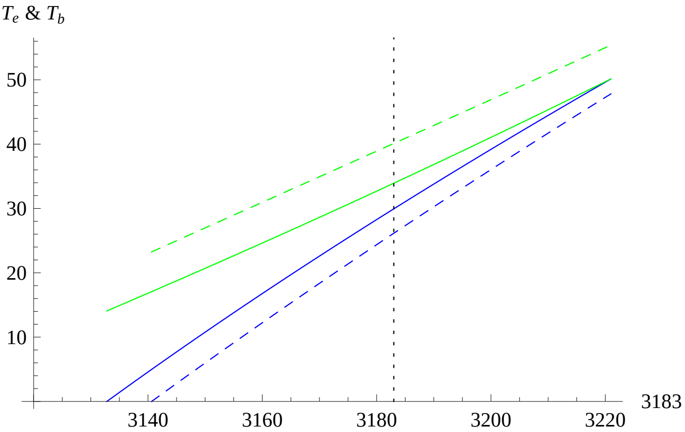


Figure: Switching dates T_e (blue) and T_b (green) as functions of the value of the ceiling in the reference case (solid line) and the constrained case (dotted line) when the marginal local damage is large

Simulations (4)

A moratorium on shale gas development

- Electricity generated with coal or solar only.
- Large local damage and lenient climate policy ($\overline{Z} > \overline{Z}_1$): the moratorium leads to the optimal solution. Inconsequential.
- Other cases: for a given climate policy, the moratorium brings forward the switch to solar and increases energy expenditures
- For a large local damage $d = 66.3 * (3/4)$, the switch to solar occurs 2 years earlier, energy expenditures increase by 1.8% and intertemporal welfare decrease by 3.6%. Very moderate effect.
- For a small local damage $d = 66.3 * 0.4$, the switch to solar occurs 30 years earlier, energy expenditures increase by 26.7% and intertemporal welfare decrease by 33.5%. Now the negative effect of the moratorium is massive.

For future research

- Impact of the subsoil property rights regime on the decision to develop shale gas.
- NIMBY effects in densely populated areas.
- Reasons why in France, not only the *exploitation* of shale gas is banned, but also *exploration* of potential reserves.
- Two country model, one with a ceiling constraint and the other without. What happens if the first one substitutes shale gas to coal at home and exports its coal?
- Energy security.
- ...