TD 6: Thermodynamics of Climate and Renewable Energies

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1 Solar Power In this exercise we estimate the Solar power and what energy we can extract.

1. By comparing the heat you feel from a 100 W light bulb and from the Sun, give an order of magnitude of the power $\mathcal{P}_S$ emitted by the Sun.
2. By dimensional analysis, find the Wien law which relates the temperature of the Sun T_S and the main wave length of emission λ_m.
3. By dimensional analysis, find the Stephan-Boltzmann law which relates the temperature of the Sun T_S and the emission power $\mathcal{P}_S$.
4. The surface temperature of the Sun is $T_S \approx 6 \cdot 10^3$ K and its radius is $R_S \approx 7 \cdot 10^8$ m. Given that Stephan's constant is $\sigma \approx 5.7 \cdot 10^{-8}$ usi, deduce $\mathcal{P}_S$.
5. Deduce the power received by the Earth $\mathcal{P}_{SE}$ and the power received by surface unit p_{ST}. For the latitude of France, p_{ST} ranges between 100 and 150 $\mathrm{W/m^2}$.
6. Considering that we cover 1% of France surface by solar panels, what is the power received?
7. You have seen that the PN junction has a maximal efficiency which is the Shockley-Queisser limit and is about 30%. Taking this into account, what is the maximal solar power we may imagine to extract? For comparison, the energy consumption in France is ≈ 300 GW and the solar energy production is ≈ 1 GW.
8. Considering that 10% of the surface of the Earth is made of plants and that photosynthesis has an efficiency of $\approx 10\%$, estimate the power obtained by photosynthesis.
9. What is the need of energy to provide food to the whole population. For comparison the agriculture provide typically $\sim 10^{12}$ W and the total resources in biomass ares estimated to $\sim 10^{13}$ W.

2 Minimal Model of Climate In this exercise we propose a small model to describe the climate. This model is composed of the Earth and an atmosphere receiving a power from the Sun. The three of them are modeled as black bodies. The Sun light reach the Earth and is partly reflected with a coefficient, the albedo, a. The Earth radiates toward the space but a fraction b of this radiation is captured by the atmosphere. Finally, the atmosphere which radiate both toward the Earth and space.

1. We denote T_A the temperature of the atmosphere and T_E the temperature of the Earth. Write the thermal balances of the Earth and the atmosphere.
2. Solve these equations for T_E.
3. The albedo a is depending on T_E, why?
4. Let us assume a to be small for $T_E > T_f = 273$ K and large for $T_E < T_f$. Draw the diagram of the dynamics of T_E.
5. Give an estimate of T_E using that the albedo is $a \approx 1/3$ and the greenhouse effect is $b \sim 0.9$. Discuss the climate change.
6. (Bonus) Make the entropic balance of the Earth.

3 Hydropower We now estimate the resources in hydropower. We denote ϕ the height of water which falls in average and by unit time and unit surface. We consider the cycle of water.

1. The whole cycle originates from the solar radiations. What is the power used to generate this cycle of water? Give an estimate.
2. This water is then stored in clouds, thus this energy becomes a potential energy. Estimate this potential energy flux and the efficiency of the cycle of water.
3. Estimate the Carnot efficiency and the Curzon-Ahlborn efficiency to comment this result.
4. Give an estimate of the resources in hydropower. For comparison is global hydroelectricity production is ≈ 1.3 TW and the global energy consumption is ≈ 18 TW.
5. The average height of France is 375 m. Estimate the hydropower resources of France. For comparison, the energy consumption in France is ≈ 300 GW and the solar energy production is ≈ 25 GW.

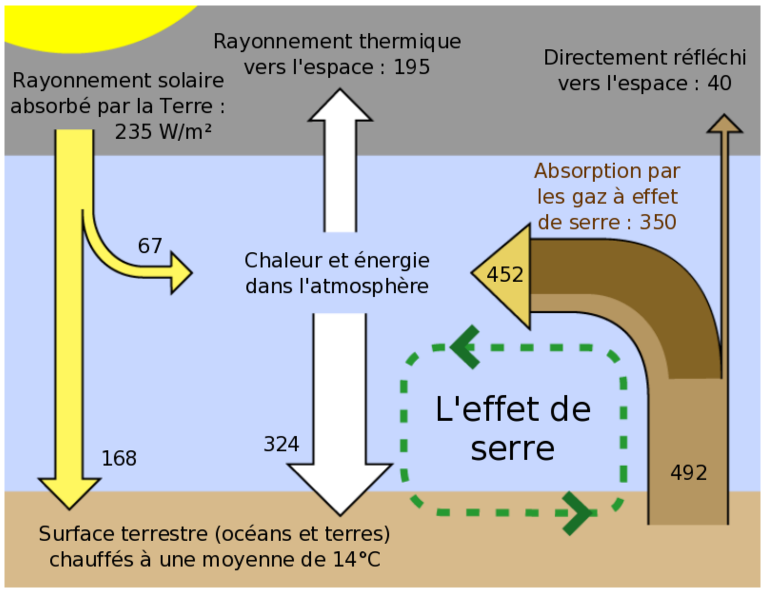

Figure 1: Schematic of the thermodynamics of climate. The figures are the real ones then not the estimations of the exercise. Picture from Wikipedia.

4 Wind power We now estimate the resources in wind.

1. Calculate the mass of the atmosphere.
2. We assume the atmosphere to be homogeneous. What is the kinetic energy of the winds? Give an estimate.
3. What is the typical time for the change of winds?
4. Give an estimate of the resources in wind power. For comparison is global wind power production is ≈ 0.2 TW and the global energy consumption is ≈ 18 TW.
5. Estimate the hydropower resources of France taking the hypothesis of covering 1% of the surface of wind turbines. For comparison, the energy consumption in France is ≈ 300 GW and the wind power production is ≈ 5 GW.

——— *Only when you have finished all the exercises* ———

The Wikipedia Moment. WILLIAM THOMSON, LORD KELVIN (1824-1907).

William Thomson's father, James Thomson, was a teacher of mathematics and engineering at the Royal Belfast Academical Institution and the son of a farmer. James Thomson married Margaret Gardner in 1817. William and his elder brother James were tutored at home by their father. James was intended to benefit from the major share of his father's encouragement, affection and financial support and was prepared for a career in engineering.

In 1832, his father was appointed professor of mathematics at Glasgow and the family moved there in October 1833. The Thomson children were introduced to a broader cosmopolitan experience than their father's rural upbringing, spending mid-1839 in London and the boys were tutored in French in Paris. Much of Thomson's life during the mid-1840s was spent in Germany and the Netherlands.

Thomson became intrigued with Fourier's Théorie analytique de la chaleur and committed himself to study the "Continental" mathematics resisted by a British establishment still working in the shadow of Sir Isaac Newton. The book motivated Thomson to write his first published scientific paper, defending Fourier, and submitted to the Cambridge Mathematical Journal by his father.

While on holiday with his family in Lamlash in 1841, he wrote a third, more substantial paper On the uniform motion of heat in homogeneous solid bodies, and its connection with the mathematical theory of electricity. In the paper he made remarkable connections between the mathematical theories of heat conduction and electrostatics, an analogy that James Clerk Maxwell was ultimately to describe as one of the most valuable science-forming ideas.

William's father was able to make a generous provision for his favourite son's education and, in 1841, installed him, with extensive letters of introduction and ample accommodation, at Peterhouse, Cambridge. The study of mathematics, physics, and in particular, of electricity, had captivated his imagination. In 1845, Thomson graduated as Second Wrangler.

In 1845, he gave the first mathematical development of Michael Faraday's idea that electric induction takes place through an intervening medium, or "dielectric", and not by some incomprehensible "action at a distance". It was partly in response to his encouragement that Faraday undertook the research in September 1845

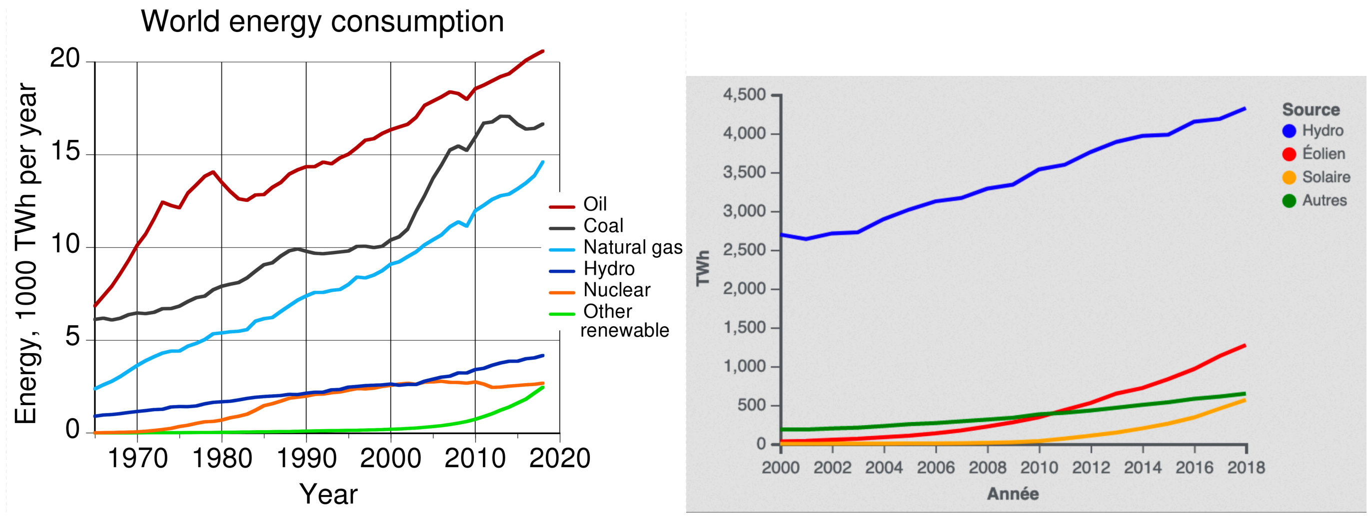

Figure 2: Evolution of energy consumption and renewable energy production in the world. Units: 1000TWh/year ≈ 0.12 TW. Graph A from "BP Statistical Review of world energy" and graph B from the International Energy Agency.

that led to the discovery of the Faraday effect, which established that light and magnetic (and thus electric) phenomena were related.

In 1846 he was appointed to the chair of natural philosophy in the University of Glasgow. By 1847, Thomson had already gained a reputation as a precocious and maverick scientist when he attended the British Association for the Advancement of Science annual meeting in Oxford. At that meeting, he heard James Prescott Joule making yet another of his, so far, ineffective attempts to discredit the caloric theory of heat and the theory of the heat engine built upon it by Sadi Carnot and Émile Clapeyron. Joule argued for the mutual convertibility of heat and mechanical work and for their mechanical equivalence.

Thomson was intrigued but sceptical. Though he felt that Joule's results demanded theoretical explanation, he retreated into an even deeper commitment to the Carnot–Clapeyron school. In 1848, he extended the Carnot–Clapeyron theory further through his dissatisfaction that the gas thermometer provided only an operational definition of temperature. He proposed an absolute temperature scale in which a unit of heat descending from a body A at the temperature T of this scale, to a body B at the temperature T-1, would give out the same mechanical effect (work), whatever be the number T. By employing such a "waterfall", Thomson postulated that a point would be reached at which no further heat (caloric) could be transferred, the point of absolute zero about which Guillaume Amontons had speculated in 1702. But a footnote signalled his first doubts about the caloric theory, referring to Joule's very remarkable discoveries. When Joule eventually read it he wrote to Thomson, claiming that his studies had demonstrated conversion of heat into work but that he was planning further experiments.

Thomson returned to critique Carnot's original publication and read his analysis to the Royal Society of Edinburgh in January 1849, still convinced that the theory was fundamentally sound. However, though Thomson conducted no new experiments, over the next two years he became increasingly dissatisfied with Carnot's theory and convinced of Joule's. In February 1851 he sat down to articulate his new thinkin During his rewriting, he seems to have considered ideas that would subsequently give rise to the second law of thermodynamics. In Carnot's theory, lost heat was absolutely lost but Thomson contended that it was "lost to man irrecoverably; but not lost in the material world". In final publication, Thomson retreated from a radical departure and declared "the whole theory of the motive power of heat is founded on ... two ... propositions, due respectively to Joule, and to Carnot and Clausius."

As soon as Joule read the paper he wrote to Thomson with his comments and questions. Thus began a fruitful, though largely epistolary, collaboration between the two men, Joule conducting experiments, Thomson analysing the results and suggesting further experiments. The collaboration lasted from 1852 to 1856, its discoveries including the Joule–Thomson effect, sometimes called the Kelvin–Joule effect, and the published results did much to bring about general acceptance of Joule's work and the kinetic theory.

In 1892, Thomson became Baron Kelvin, of Largs in the County of Ayr. In November 1907 he caught a chill and his condition deteriorated until he died at his Scottish country seat, Netherhall, in Largs on 17 December. During his career, Thomson published more than 650 scientific papers and applied for 70 patents (not all were issued).

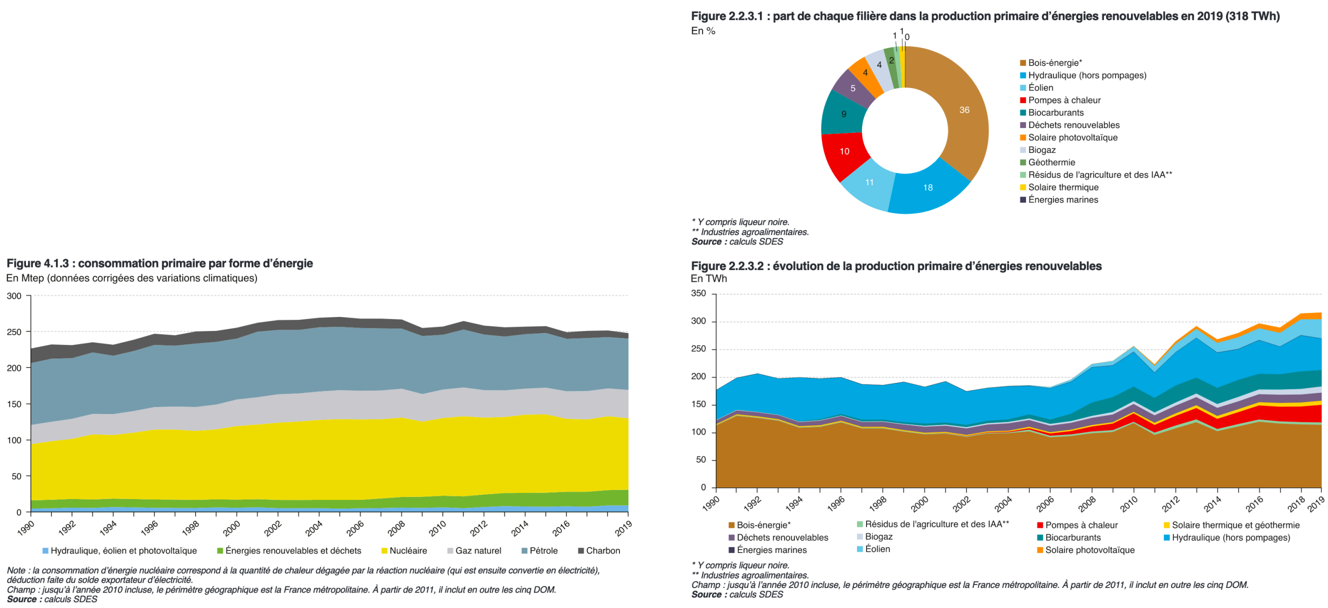

Figure 3: Evolution of energy consumption and renewable energy production in France. Units: 1Mtep/year ≈ 1.4 GW and 1TWh/year ≈ 0.12 GW. Graph from "Bilan énergétique de la France pour 2019", Ministère de l'Écologie.

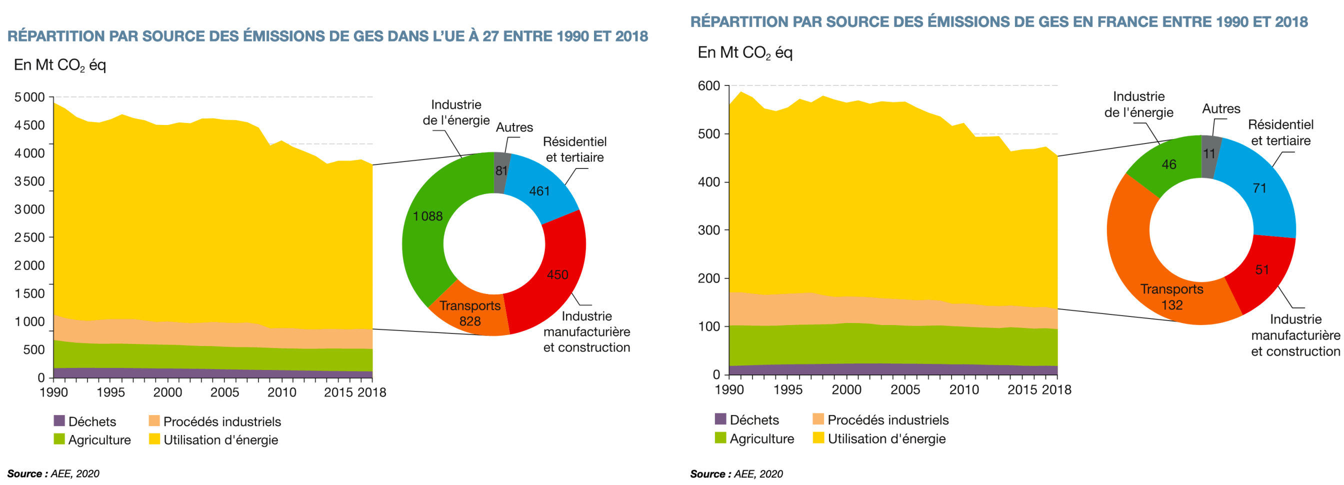

Figure 4: Greenhouse gas emissions respectively of the EU and France. Source: Ministère de l'Écologie.

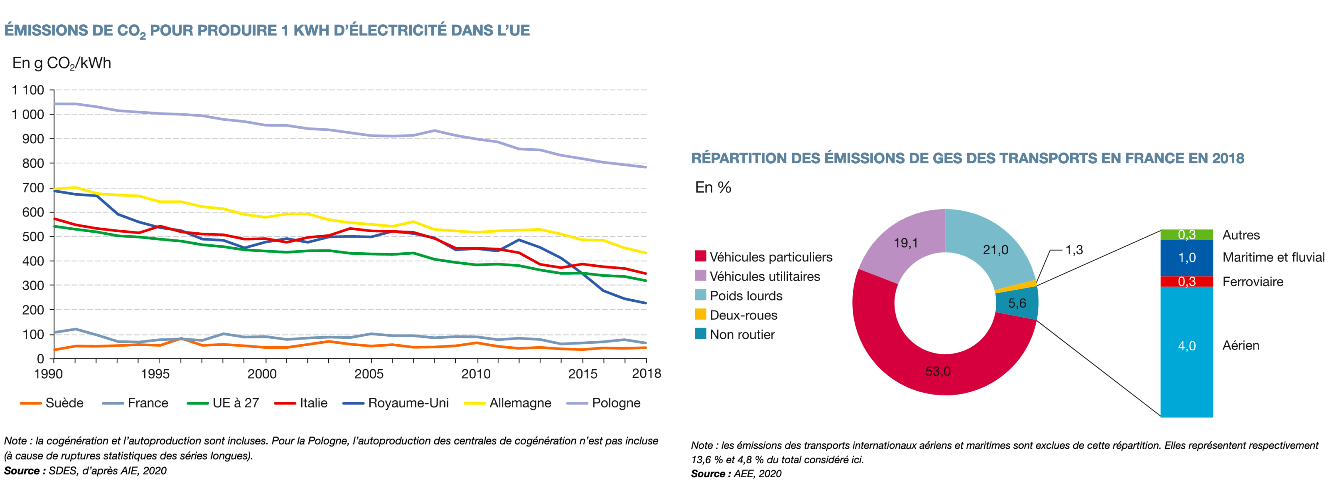

Figure 5: A: Comparison of the carbon emissions for the electricity production inside the EU. For France, he electricity has a low carbon impact, so that the most polluting sector is the transport sector. B: Details of the greenhouse gas emissions of the transport sector in France. Source: Ministère de l'Écologie.