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From phase transition to energy transition: What can we learn from physics?

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Abstract

In order to better understand the energy transition, we develop an analogy with phase transitions in physics. Phase transitions are triggered by the variation of a state variable at the transition point: a dramatic qualitative modification occurs. For the energy system, we use a TIMES bottom-up model that optimizes the pathway of this system. By analogy, we consider a pathway of the energy system as a phase in physics and the total discounted cost of the energy system as the Gibbs free energy. In physics, the transition between two phases is possible if their Gibbs free energies have the same value. Likewise, the transition between two pathways of the energy system is possible if their costs are similar. By applying this methodology to the French energy system we exhibit a transition between two pathways with different electricity mixes.

Keywords: phase transition and stability; energy system; prospective; decarbonization pathways

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1. Introduction

What do we mean by transition? The word is used today to describe many phenomena, such as demographic, social, digital and energy transitions. In physics, a phase transition is usually associated with a sudden change in a system triggered by the modification of a control parameter.

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Beyond perception and common sense about the notion of transition, the phase transition theory has been widely developed and analyzed in physics for over a century [1]. It was first developed to explain the abrupt change of magnetic order in magnets [2], [3] and was then enhanced by cross-fertilization with thermodynamics and statistical physics. In particular, statistical physics showed that some "universal" features exist that in fact depend on a few characteristics:

- Dimension of the system;
- Number of degrees of freedom of microscopic objects in interactions;
- Range of microscopic interactions.

Ideally, this theory is used within a macroscopic limit (the so-called "thermodynamic limit"), which means that the number of interacting microscopic objects tends to infinity. These "universal" laws make it possible to describe a system without considering all of its details.

Thus phase transitions can be identified in very different contexts, and the associated models have been used in many fields outside of physics. [4] highlights the role of phase transitions in the emergence of collective phenomena in social sciences, such as the dynamics of voting, traffic jams and cultural segregations in human populations. We can also cite its use in marketing [5] and economics [6]. [7] presents other examples of application, including in biology: the spread of epidemics, gene networks and virus dynamics. Many more examples can be found in ecology [8], game theory [9] and cosmology [10]. All of these models involve a large number of actors or elements for which we want to analyze a break in their average behavior. Despite the local nature of interactions between individual agents and the absence of global coordination, the emergence of collective behaviors as phase transitions can still be observed.

The physics of phase transitions provides an interesting theoretical framework in the context of climate change. When we talk about the transition of the energy system, which is a particularly complex system, change does not tend to be a linear process. To achieve a reduction of greenhouse gas emissions by a factor of 4 as enacted in August 2015 into the French Green Energy Transition Law for Green Growth [11], or even carbon neutrality, will require significant changes in the energy system: such an extensive reduction of emissions implies profound and important modifications in all sectors and some threshold effects could appear. We can thus analyze the energy transition with the insights provided by statistical physics and speculate whether any characteristic phase transition phenomena might appear, such as abrupt shifts or critical points.

2. Methodology

2.1. Phase transitions in physics

The physics of phase transitions provides a relevant conceptual framework for studying energy transitions. A phase is a homogeneous part (i.e. with uniform physical properties) that is physically distinct from the other phases of the system it belongs to. During a phase transition, the system goes from one phase to another, each of which has specific properties. Phase transitions are characterized by a discontinuity of some properties of the studied system: the variation of a control parameter (e.g. the temperature) at the transition point triggers a dramatic qualitative modification [12].

In the context of thermodynamics, the study of phase transitions rely conveniently on the variational analysis of the Gibbs potential, whose minimum defines the thermodynamic equilibrium and provides the Gibbs free-energy. This Gibbs free energy is the state function of the system depending on state variable (for instance the temperature). One model that is rich enough to describe a phase transition, and simple enough to allow approximate or exact resolution methods [13], is the Ising model [14]. It was developed as part of the study of paramagnetic-ferromagnetic transitions. A variational analysis of the Gibbs potential (or thermodynamic functional) shows that a phase transition corresponds to a competition between the (magnetic) order energy and the (entropic) disorder energy, between a ferromagnetic ordered phase where all of the spins aspire to the same magnetization at low temperature (i.e. low entropy), and a disordered phase at high temperature (i.e. high entropy). This transition is associated with a symmetry breaking: the system moves towards greater symmetry in the disordered phase. This thermodynamic singularity is a key feature of phase transitions [15].

More generally, the transition is accompanied by a loss of analyticity of the Gibbs free-energy from which the macroscopic properties of the system are derived. More precisely, by minimizing the Gibbs potential $\mathscr{F}$ according to an order parameter *m* characterizing the symmetry of the system (often derived from ground state analysis), we can obtain the states accessible by the system. Phase transitions occur differently depending on whether they are first-order or second-order. For first-order transitions, the Gibbs free energies of the two phases are equal at the transition point so that both phases can coexist at the same time (see Fig. 1). This is the case for instance when we melt ice to obtain water and the transition can be monitored by the ratio of one phase to the other one. For second-order transitions, there is only one value for the free energy at the transition point, which means that the transition can occur continuously from one phase to another, with the discontinuity in the Gibbs free energy occurring for a second derivative (see Fig. 2).

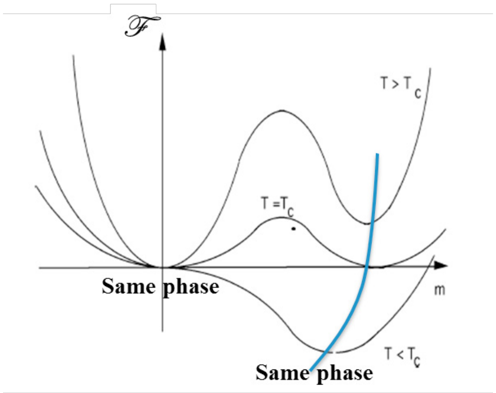

Fig. 1 Schematic representation of the Gibbs potential for first-order transition for different temperatures, T_c is the transition point

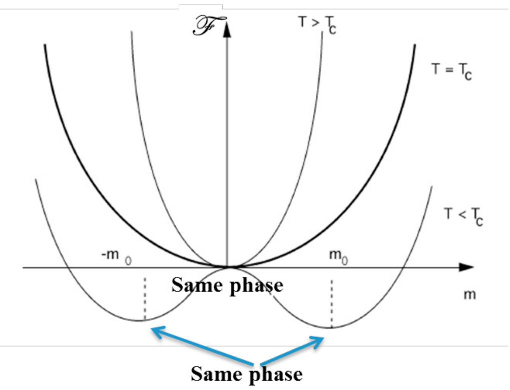

Fig. 2 Schematic representation of the Gibbs potential for second-order transition for different temperatures, T_c is the transition point

Since the Gibbs potential varies with the values of the macroscopic parameters, we obtain different values of the order parameter that minimize the Gibbs potential and that lead to the same value of the Gibbs free energy. The evolution of this order parameter as a function of macroscopic parameters characterizes the order of the phase transition. For first-order transitions, the Gibbs potential is bi-valued at the transition leading to a discontinuity in the evolution of the order parameter, whereas for second-order transitions (or critical transitions), the two minima of the Gibbs potential merge together at the transition and the order parameter varies continuously, defining a critical point. These are the ingredients that we will seek to transpose in the context of energy systems.

2.2. Towards the use of phase transitions to characterize energy transition

In order to study the evolutions of the energy system, we use the TIMES-FR model. It is a long-term planning bottom-up model from the MARKAL/TIMES family for the French energy system. This approach is based on the optimization of a technical-economic representation of the energy system [16]. The model minimizes the total discounted cost over the whole horizon and identifies optimal investment and operation decisions from an available set of processes and commodities. The results of this optimization therefore include a trajectory of the energy system with the energy mix and the associated emissions.

For the analogy with the physics of phase transitions (see Table 1), we associate with the notion of phase in physics a set of energy system trajectories given by the TIMES model, whose main parameters are similar, that is to say whose energy mixes are similar. In the same way that a state of a system in physics is defined by its minimum of the Gibbs potential, that is to say its Gibbs free energy, the trajectory of the energy system is defined by the minimization of the total discounted cost. To evaluate the stability of a trajectory and therefore consider that it is easily identifiable at one phase, we can introduce a small perturbation in the model (e.g. increased energy costs) and check whether the trajectory has been modified. If it has not, we can conclude that the state is stable. The TIMES model thus makes it possible to obtain sets of trajectories that we can group in different phases. A transition between two phases will be allowed if the total discounted cost (playing the role of free energy) is similar for two different trajectories (or two states).

Table 1 Analogy between phase transitions and energy transitions

Phase transition	**Energy transition**
State of the system: defined by macroscopic parameters For instance: (P, V, T) defines the state of water.	State of the system: the trajectory of the energy system defined by its installed capacities or its energy supply
A phase is a set of states whose physical properties are uniform.	A phase is a set of trajectories of the energy system whose characteristics are similar (for instance, same emission level).
Gibbs free energy (minimum of the Gibbs potential)	Total discounted cost (minimum)
Gibbs potential (Thermodynamic functional)	Functional of the total discounted cost

3. One example of phase transition in energy transition

Using the TIMES-FR model, we can obtain two paths of the energy system differentiated by their set of constraints. The first scenario, ScenCO2, must result in an 80% reduction of CO_2 emissions in 2050 compared to 1990. The second scenario, ScenCO2_Elc, in addition to the same constraint, must satisfy a minimum share of renewable energy and a maximum share of nuclear power in the electricity production. All of the other parameters, like renewable potential, cost, CO_2 tax, etc., are identical.

The results show that the costs of both scenarios are very similar since the relative difference between their total discounted costs is about 1%. However, if we compare their electricity production (see Fig. 3), we observe significant discrepancies in the output. In the scenario ScenCO2, the share of decarbonized electricity in total production is greater than in the other scenario (10% more in 2050).

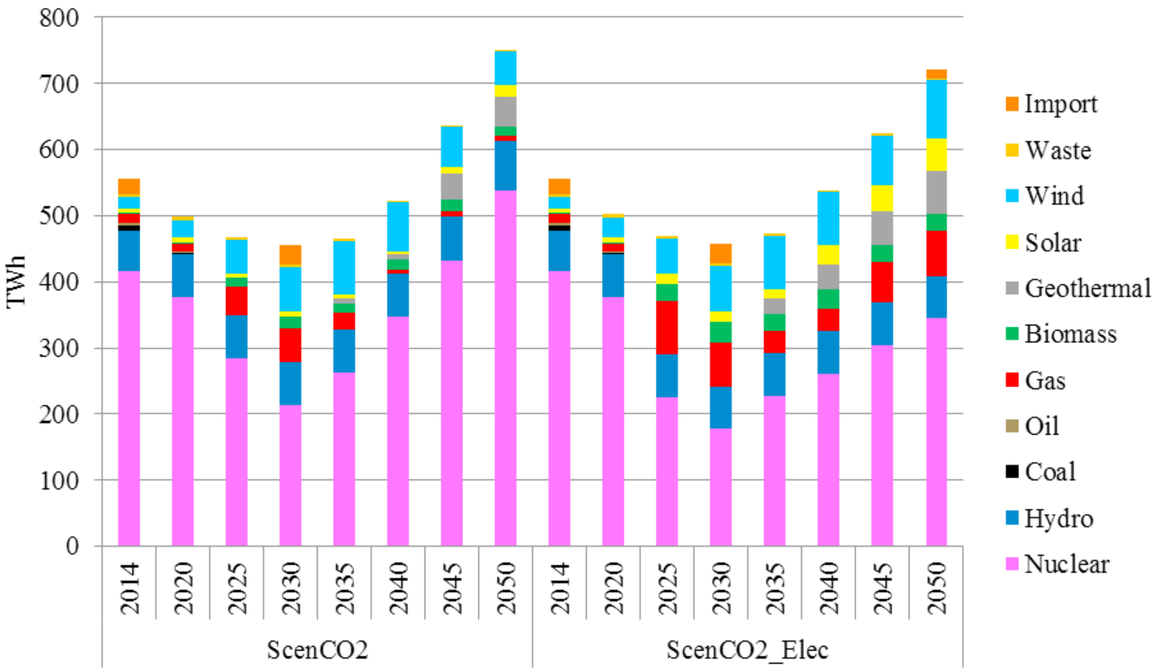

Fig. 3 Electricity production

This result is also reflected in the installed capacities as we can see in Fig. 4. The installed nuclear capacities are much more significant in ScenCO2 (81 GW in 2050) than in ScenCO2_Elc (52GW in 2050). The two electrical systems, which were similar at the beginning, are different at the end of the horizon (2050).

In order to show that the paths of the two scenarios are stable, we can introduce small disturbances: we modified the REN and nuclear costs with a lower version for REN cost (EnrLow) and a higher version for nuclear (NucHigh). The results for installed capacities in ScenCO2_Elc show only slight differences as we can see in Fig. 5. We can make the same observations for electrical production and also for the other scenario ScenCO2 and its variants.

By analogy with the physics of phase transitions, where the thermodynamic functional can be minimized for two values, we can consider that since the total discounted cost of each scenario is very similar, the planner "has a choice" between two states that belong to two different phases (the electrical system is very different according to the considered scenario). Put another way, the energy system can transition from one electrical system dominated by nuclear power to another system where its share is limited. This type of transition can be assimilated to a first-order transition. It could imply that hysteresis effects or abrupt shifts might occur.

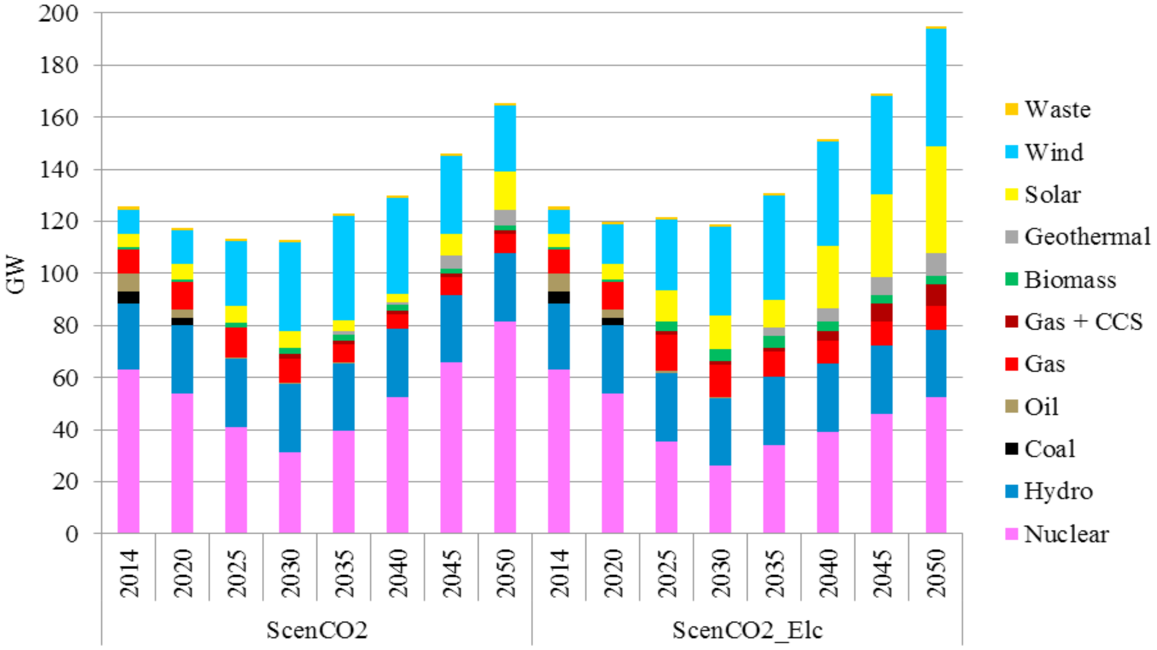

Fig. 4 Electrical capacities

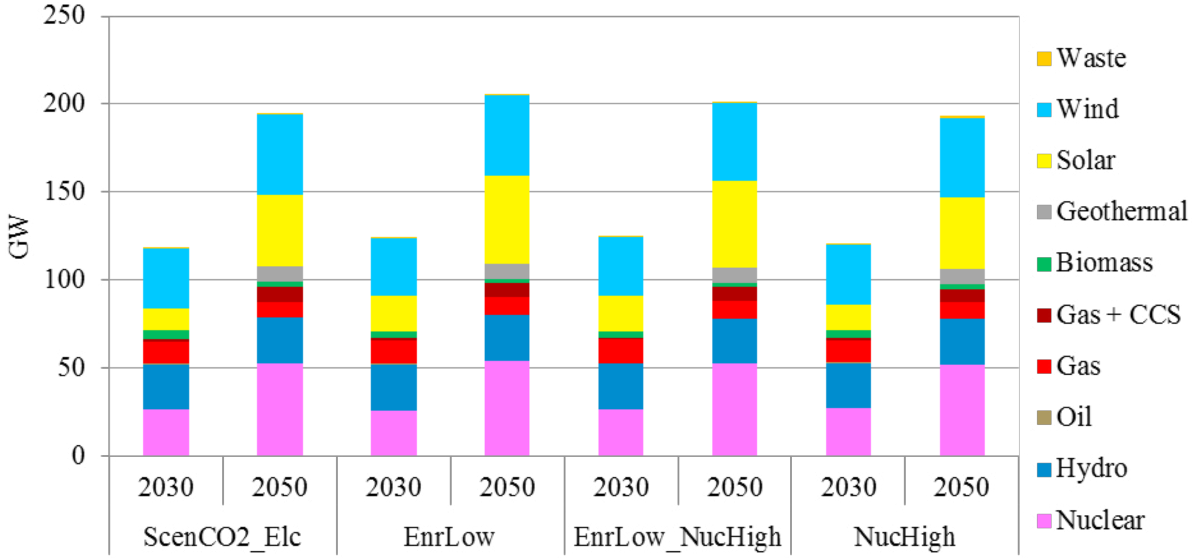

Fig. 5 Electrical capacities with different ENR and nuclear costs

4. Conclusion

To make a transition in physics, variations of macroscopic variables cause a dramatic qualitative change in the physical system. With our analogy, in the case of energy systems, the energy transition is only possible if the total discounted cost is similar. In our example, we showed the existence of two pathways that belong to two different phases, which have nearly the same cost. However, we have to seek their coexistence point according to a macroscopic parameter which will be the point of transition. In the proposed example, the macroscopic parameter corresponds to the appearance of an additional constraint in the production of electricity. This constraint change does not correspond to the continuous variation of a control parameter that would trigger the transition. Further analysis will require reflecting on the definition of such a parameter by using the duality theory of optimization problems and the implications of the existence of first-order transition (e.g. sudden shift or hysteresis) or studying the possibility of the existence of second-order transition.

Moreover, we can apply this framework of analysis to other countries, such as Germany, whose current transition is experiencing some difficulties since numerous experts have announced that the country will miss its climate targets for 2020. We will try to determine whether the envisaged transition is truly possible.

References

[1] C. Domb, M. S. Green, and J. L. Lebowitz, Eds., *Phase transitions and critical phenomena. Vol. 1: Exact results*, 2. print. London: Acad. Press, 1976.
[2] P. Curie, “Propriétés magnétiques des corps à diverses températures,” *Ann Chem Phys*, vol. 5, pp. 289–405, 1895.
[3] P. Langevin, “Sur l’origine des radiations et l’inertie électromagnétique,” *J. Phys. Théorique Appliquée*, vol. 4, no. 1, pp. 165–183, 1905.
[4] P. Ball, “The Physical Modelling of Human Social Systems,” *Complexus*, vol. 1, no. 4, pp. 190–206, Dec. 2004.
[5] J.-P. Nadal and M. B. Gordon, “Physique statistique de phénomènes collectifs en sciences économiques et

sociales," *Mathématiques Sci. Hum. Math. Soc. Sci.*, no. 172, Dec. 2005.
[6] S. Bornholdt and F. Wagner, "Stability of money: phase transitions in an Ising economy," *Phys. Stat. Mech. Its Appl.*, vol. 316, no. 1, pp. 453–468, Dec. 2002.
[7] R. V. Solé, *Phase transitions*. Princeton, N.J: Princeton University Press, 2011.
[8] M. Scheffer and S. R. Carpenter, "Catastrophic regime shifts in ecosystems: linking theory to observation," *Trends Ecol. Evol.*, vol. 18, no. 12, pp. 648–656, Dec. 2003.
[9] D. Helbing and S. Lozano, "Phase transitions to cooperation in the prisoner's dilemma," *Phys. Rev. E*, vol. 81, no. 5, p. 057102, May 2010.
[10] L. S. Schulman and P. E. Seiden, "Percolation and galaxies," *Science*, vol. 233, no. 4762, pp. 425–431, Jul. 1986.
[11] French Government, *LOI n° 2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte*. 2015.
[12] M. Héritier, *Physique de la matière condensée: Des atomes froids aux supraconducteurs à haute température critique*. EDP Sciences, 2013.
[13] L. Onsager, "Crystal Statistics. I. A Two-Dimensional Model with an Order-Disorder Transition," *Phys. Rev.*, vol. 65, no. 3–4, pp. 117–149, Feb. 1944.
[14] E. Ising, "Beitrag zur Theorie des Ferromagnetismus," *Z. Für Phys.*, vol. 31, no. 1, pp. 253–258, Feb. 1925.
[15] L. D. Landau, "On the theory of phase transitions," *Ukr J Phys*, vol. 11, pp. 19–32, 1937.
[16] R. Loulou, G. Goldstein, A. Kanudia, A. Lettila, and U. Remme, "Documentation for the TIMES Model Part I: TIMES concepts and theory," ETSAP, Jul. 2016.