Chapter 3
On the Dynamics of the Deployment of Renewable Energy Production Capacities

R. Fonteneau and D. Ernst

Abstract This chapter falls within the context of modelling the deployment of renewable energy production capacities in the scope of the energy transition. This problem is addressed from an energy point of view, i.e., the deployment of technologies is seen as an energy investment under the constraint that an initial budget of nonrenewable energy is provided. Using the Energy Return on Energy Investment (ERoEI) characteristics of technologies, we propose MODERN, a discrete-time formalization of the deployment of renewable energy production capacities. Besides showing the influence of the ERoEI parameter, the model also underlines the potential benefits of designing control strategies for optimizing the deployment of production capacities and the necessity to increase energy efficiency.

Keywords Modelling • Renewable energy • Energy transition • ERoEI • Discrete-time • Dynamical systems

3.1 Introduction

The relations linking energy consumption and societies' prosperity have been thoroughly investigated in the last decades. It has progressively become clear that energy has played a decisive role in societies' demographic and economic development (Meadows et al. 1972; Cleveland et al. 1984; Lambert et al. 2012; Giraud and Kahraman 2014), as well as in their decline (Tainter 1988).

About 85 % of world energy consumption is currently from nonrenewable origin, most of which being fossil fuels such as coal, oil, and gas. The "energy transition," which is the shift to a world that would no longer virtually rely on nonrenewable energy resources, is a crucial challenge of the twenty-first century for two main reasons: (1) the massive consumption of fossil fuels has major environmental impacts, mainly pollution and greenhouse effect gas emissions, and (2) there

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is convincing evidence that even putting aside these environmental concerns our societal lifestyle cannot be sustained without changing our energy production and consumption habits.

One of the main difficulties of this transition comes from the fact that switching to an energy system that would not depend on nonrenewable resources is a process that itself needs—at least for the moment—to use nonrenewable energy. For instance, in 2013, about half of photovoltaic panels have been produced in China (Jäger-Waldau 2013) whose own energy production mix was around 70 % from coal in 2011 (US Energy Information Administration 2015), which suggests that the rise of PV energy over the last 10 years was mainly achieved through using nonrenewable energy resources.

In this chapter, we propose to consider the deployment of renewable energy production capacities as an energy investment. This point of view is motivated by the fact that the ERoEI parameters characterizing the two main rising renewable technologies—wind turbines and photovoltaic panels—are currently too low to be negligible (Murphy and Hall 2010). We propose MODERN (for "MOdelling" the Deployment of Energy production from "ReNewable" resources), a discrete-time model that aims at simulating the deployment of renewable energy capacities in the context of the depletion of a given budget of nonrenewable resources. MODERN makes use of ERoEI characteristics of technologies that relate the energy produced to the energy invested together. MODERN can be controlled using growth scenarios for the deployment of the production capacities. We illustrate some typical runs of MODERN in the context of ERoEI corresponding to photovoltaic panels. In particular, we observe how the availability of nonrenewable energy can actually boost the growth of production capacities and eventually create a "bubble effect"; we show that this bubble may be mitigated using control strategies.

The following of this chapter is organized as follows: Section 3.2 provides ERoEI notions. Section 3.3 presents MODERN, our discrete-time formulation of the deployment of renewable energy production capacities. Section 3.4 illustrates several typical runs of MODERN with a parameterization matching the deployment of photovoltaic panels. Section 3.5 discusses how MODERN opens the door to the use of control strategies in the context of the energy transition. Section 3.6 provides a discussion about the link between energy and societies' GDP and emphasizes reasons why the deployment strategies of renewable energy production capacities should be carefully designed. Section 3.7 concludes this chapter.

3.2 Energy Return on Energy Investment

Energy Return on Energy Investment (ERoEI) is a notion that was probably first coined in the works of Cleveland et al. (1984) and Hall et al. (1986). It is defined as the ratio of the amount of final usable energy acquired from a particular energy resource to the amount of primary energy expended to obtain that energy resource:

$$\text{ERoEI} = \frac{\text{Usable Acquired Energy}}{\text{Energy Expended to Get that Energy}} \tag{3.1}$$

More specifically, this ratio—supposed to be dimensionless—means that a given energy production technology will provide ERoEI Joules (J) on an energy investment of 1 J. Note that computing ERoEI for a given energy production technology may be a complex task because it implies a rigorous definition of system boundaries (energy inputs, energy outputs), as well as accurate evaluation of energy costs in between these boundaries. In particular, the natural or original sources of energy are usually not taken into account. For instance, the energy consumed by the sun to produce light is not taken into account in the computation of the ERoEI of photovoltaic technologies. We refer to the work of Murphy and Hall (2010) for a solid review of the work that has been done around the notion of ERoEI. We provide hereafter in Fig. 3.1 a graph of ERoEI values for a panel of technologies in the specific case of the USA (figures taken from Murphy and Hall 2010).

This graph illustrates different aspects of the ERoEI. One can first observe that the ERoEI of US oil and gas productions has declined over time, from about 30 in the 1970s to about 15 in 2005. This is easily explained by the fact that oil and gas fields that were the easiest to exploit were exploited first. This graph also shows that hydroelectricity has a very high ERoEI (above 100). One may also observe that energy production from coal has a high ERoEI (in the order of 80). The ERoEI value of photovoltaic panels (around 10) has a rather low value here compared to other renewable energy sources such as hydroelectricity (more than 100) or wind turbines (around 18). Observe however that photovoltaic panels technology is

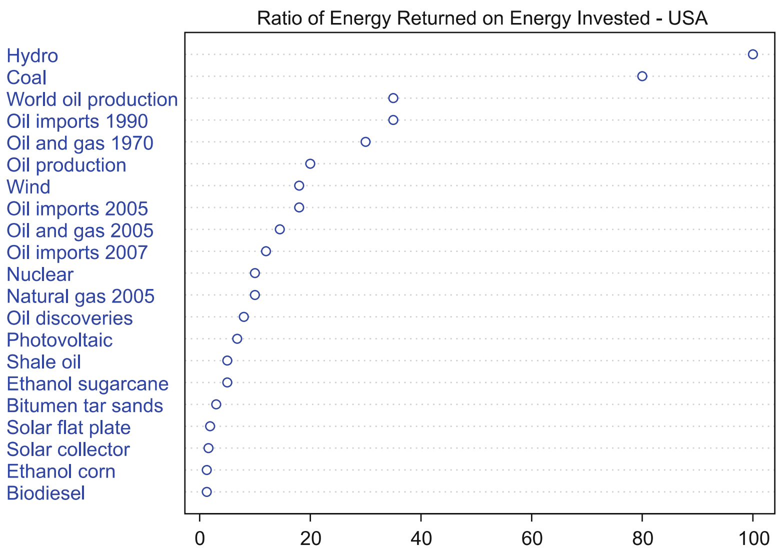

Fig. 3.1 ERoEI of several technologies in the USA—data source: (Murphy and Hall 2010)—image taken from Wikipedia

progressing, and that it might be possible that its ERoEI will increase significantly in the coming years. Finally, even if nuclear energy is reported to have an ERoEI of about 16, it is important to notice that this technology is among those for which the ERoEI computation is the most uncertain (Lambert et al. 2012).

3.3 MODERN: A Discrete-Time Model of the Deployment of Renewable Energy Production Capacities

This section introduces all the elements of MODERN, a discrete-time model of the deployment of energy production capacities from renewable sources and the multiple assumptions upon which it is built. For clarity, we assume that all variables considered in this chapter are deterministic.

3.3.1 Time

We consider a discrete-time system, where each time-step corresponds to 1 year:

$$t = 0 \ldots T - 1 \tag{3.2}$$

The time horizon is in the order of hundreds of years:

$$T \sim 100 - 500 \tag{3.3}$$

3.3.2 Assumption Regarding the Energy Produced from Nonrenewable Sources

We assume that each year, a quantity of nonrenewable energy is available:

$$\forall t \in \{0, \ldots, T-1\}, \quad B_t \geq 0 \tag{3.4}$$

By nonrenewable energy, we mean fossil fuel energy (coal, oil, and gas), but also nuclear energy (mainly Uranium fission). For clarity, we choose not to separate the different types of energy production technologies from nonrenewable sources. The evolution of the quantity of available nonrenewable energy is modelled using Hubbert curves (Hubbert 1956):

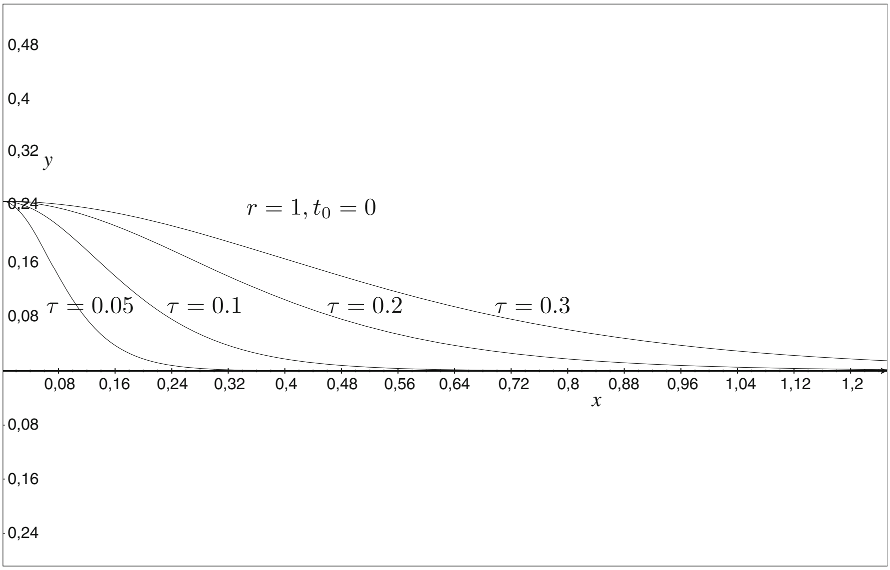

Fig. 3.2 Some Hubbert curves obtained with different values of the parameter τ

$$\exists r > 0, \;\; \exists \tau > 0, \;\; \exists t_0 \in \mathbb{R} : \forall t \in \{0, \ldots, T-1\}$$
$$B_t = \frac{1}{r} \frac{e^{-\frac{(t-t_0)}{\tau}}}{\left(1 + e^{-\frac{(t-t_0)}{\tau}}\right)^2} \tag{3.5}$$

As shown in Fig. 3.2, the role of τ is to model the level of "flatness" of the Hubbert curve. The parameter t_0 induces a time shift of the curve. For simplicity, we assume that this energy is "net," i.e., we assume that the energy required to obtain that energy is already subtracted from it. Recent papers have shown that the ERoEI related to processes producing energy from nonrenewable resources tend to decline over time (Murphy and Hall 2010). The intuition behind this is the fact that spots for which resources are easily extracted are exploited first. The Hubbert curve, which models the extraction of nonrenewable resources, reflects to a certain extend that energy is increasingly more expensive to obtain (in terms of energy investment, but also cost).

3.3.3 Energy from Renewable Origin

We assume that a set of N different technologies for producing energy from renewable sources is available. To each technology is associated a production capacity yearly producing a quantity of energy $R_{n,t}$:

$$\forall n \in \{1, \ldots, N\}, \ \forall t \in \{0, \ldots, T-1\}, \quad R_{n,t} \geq 0 \tag{3.6}$$

Among these technologies, let us (non-comprehensively) mention biomass, hydroelectricity, wind turbines, or photovoltaic panels. Two main parameters, the expected lifetime and ERoEI characterize each of these technologies:

$$\begin{aligned} \forall n \in \{1, \ldots, N\}, \ \forall t \in \{0, \ldots, T-1\}, \quad \Delta_{n,t} &\geq 0 \\ \mathrm{ERoEI}_{n,t} &\geq 0 \end{aligned} \tag{3.7}$$

Description of ERoEI is provided in Sect. 3.2. The expected lifetime parameter describes the average lifetime of equipment enabling energy production. Note that in this model, we do not consider energy production and consumption fluctuations, as well as storage issues associated with each of these technologies. In practice, providing storage capacities or technologies that allow modulating the consumption so that it matches the production (such as energy demand side management in the context of electricity grids) induces a decrease of the ERoEI parameters (e.g., building batteries to assist photovoltaic panels is an additional expanse of energy).

3.3.4 Dynamics of Deployment of Energy Production Means

The dynamics of the deployment of energy production means is modelled using a growth parameter:

$$\forall n \in \{1, \ldots, N\}, \forall t \in \{0, \ldots, T-1\}, \quad R_{n,t+1} = (1 + \alpha_{n,t}) R_{n,t} \tag{3.8}$$

Note that the growth parameter may be negative:

$$\forall n \in \{1, \ldots, N\}_1 \forall t \in \{0, \ldots, T-1\}, \quad \alpha_{n,t} \in [-1, \infty[\tag{3.9}$$

3.3.5 Energy Costs for Growth and Long-Term Replacement

We introduce the energy cost associated with the growth of the production capacities of renewable technologies:

$$\forall n \in \{1, \ldots, N\}_1, \forall t \in \{0, \ldots, T-1\}, \quad C_{n,t}(R_{n,t}, \alpha_{n,t}) \geq 0 \tag{3.10}$$

We assume that this cost also incorporates the energy required for maintenance during the lifetime of the equipment. We also introduce the energy cost associated with the long-term replacement of the production means:

$$\forall n \in \{1, \ldots, N\}, \forall t \in \{0, \ldots, T-1\}, \quad M_{n,t} \geq 0 \tag{3.11}$$

The role of this quantity of energy is to formalize the energy cost that has to be "paid" when equipment becomes obsolete and has to be replaced (see a few assumptions regarding this energy cost later in the chapter).

3.3.6 Total Energy and Net Energy to Society

Using the previous notations, we define the total energy produced at year t:

$$\forall t \in \{0, \ldots, T-1\}, \quad E_t = B_t + \sum_{n=1}^{N} R_{n,t} \tag{3.12}$$

We also define the net energy available to society:

$$\forall t \in \{0, \ldots, T-1\}, \quad S_t = E_t - \left(\sum_{n=1}^{N} C_{n,t}(R_{n,t}, \alpha_{n,t}) + M_{n,t} \right) \tag{3.13}$$

This corresponds to the amount of energy that can be used after energy investment for increasing the production capacities from renewable resources and their long-term replacement.

3.3.7 Constraints on the Quantity of Energy Invested for Energy Production

We assume that the energy investment for developing, maintaining, and replacing the production means from renewable sources cannot exceed a given fraction of the total energy. In other words, this assumption means that the ratio of net energy to society over total energy has to remain above a given threshold. Formally, we assume that:

$$\forall t \in \{0, \ldots, T-1\}, \quad \exists \sigma_t : C_{n,t}(R_{n,t}, \alpha_{n,t}) + M_{n,t} \leq \frac{1}{\sigma_t} E_t \tag{3.14}$$

In the following, we denote by "energy threshold" such a parameter. This constraint is motivated by research investigation showing that if a society invests a too high a proportion of its energy for producing energy, then less energy is dedicated to other societal needs, which may result into a decrease of the global society welfare (Lambert et al. 2012).

3.3.8 Assumptions on Growth and Replacement Energy Costs

In order to relate the energy costs associated with the deployment and the long-term replacement of the renewable energy production capacities, we make the three following assumptions:

1. The energy cost associated with the installation of new production means of technologies is proportional to the corresponding growth:

$$\forall n \in \{1,\dots,N\}, \forall t \in \{0,\dots T-1\}, \quad \exists_{\gamma_{n,t}} > 0$$
$$C_{n,t}(R_{n,t},\alpha_{n,t}) = \begin{cases} \gamma_{n,t}\alpha_{n.t}R_{n,,t} & \text{if } \alpha_{n,t} \geq 0 \\ 0 & \text{else} \end{cases} \tag{3.15}$$

2. All the energy costs related to building a production capacity and to operating it over its lifetime are allocated at the time period when this capacity starts producing energy:

$$\forall n \in \{1,\dots,N\}, \forall t \in \{0,\dots T-1\}, \quad \gamma_{n,t} = \frac{\Delta_{n,t}}{\text{ERoEI}_{n,t}}$$
$$C_{n,t}(R_{n,t},\alpha_{n,t}) = \frac{\Delta_{n,t}}{\text{ERoEI}_{n,t}}\alpha_{n,t}R_{n,t} \quad \text{if} \quad \alpha_{n,t} \geq 0 \tag{3.16}$$

3. The energy cost associated with the long-term replacement of production capacities is (1) annualized and (2) proportional to the quantity of energy produced yearly:

$$\forall n \in \{1,\dots,N\}, \;\; \forall t \in \{0,\dots T-1\}, \;\; \exists \mu_{n,t} > 0 : M_{n,t}(R_{n,t}) = \mu_{n,t}R_{n,t} \tag{3.17}$$

Using the ERoEI parameter, we get the following equations:

$$\forall n \in \{1,\dots,N\}, \;\; \forall t \in \{0,\dots T-1\}, \quad \mu_{n,t} = \frac{1}{\text{ERoEI}_{n,t}}$$
$$M_{n,t}(R_{n,t}) = \frac{1}{\text{ERoEI}_{n,t}}R_{n,t} \tag{3.18}$$

3.4 Simulation Results: Case Study for Photovoltaic Panels

We propose to simulate MODERN where only photovoltaic panels are deployed. For simplicity, we denote by one the index related to photovoltaic technology. Formally, this means that growth parameters associated to other technologies are kept constant at zero:

$$\forall n \in \{2,\dots,N\}, \forall t \in \{0,\dots T-1\}, \quad \alpha_{n,t} = 0 \tag{3.19}$$

3.4.1 Variable Initialization

We choose to consider normalized variables with respect to the total energy at time 0:

$$E_0 = 1 \tag{3.20}$$

The Hubbert curve modelling the depletion of nonrenewable energy is initially scaled so that the proportion between renewable and nonrenewable energy production matches, approximately, the current situation for 2014 (British Petroleum 2014):

$$B_0 = 0.85\,E_0 \tag{3.21}$$

The quantity of energy produced by photovoltaic panels is initially assumed to be around 1 % of the world total energy mix:

$$R_{1,0} = 0.01\,E_0 \tag{3.22}$$

This value (1 %) also corresponds, approximately, to the current proportion of energy produced by photovoltaic panels plus wind turbines in the world total energy mix. All remaining technologies producing energy from renewable sources are kept constant at their initial level, i.e.,

$$\forall t \in \{0, \ldots, T-1\}, \quad \sum_{n=2}^{N} R_{n,t} = \sum_{n=2}^{N} R_{n,0} = 0.14 E_0 \tag{3.23}$$

The constraint of the total amount of energy that may be dedicated to growing energy production means is chosen as follows:

$$\forall t \in \{0, \ldots, T-1\}, \quad \sigma_t = 14 \tag{3.24}$$

The choice of this value for the energy threshold is motivated by results reported in the literature (Lambert et al. 2012). As shown by Lambert et al., this value appears to be the smallest so that society may develop and sustain social amenities that are considered to be at the top of the “society Maslow pyramid,” such as healthcare systems and arts (see the figure “Pyramid of Energetic Needs” in Lambert et al. 2012).

3.4.2 Growth Scenario

MODERN can be controlled through the growth scenario. By growth scenario, we mean a sequence of predefined growth parameters. Formally, a growth scenario is a T-tuple of real numbers:

$$(\alpha_{1,0}, \ldots \alpha_{1,T-1}) \in \mathbb{R}^{\mathrm{T}} \tag{3.25}$$

When simulated, such scenarios may not satisfy the energy threshold constraint. If so, the growth parameter is reduced to the maximal allowed value so that it does not violate the constraint. In the case where the constraint is violated, then the growth parameter is set to the maximal value that still satisfies the energy threshold constraint defined as follows:

$$\forall t \in \{0, \ldots, T-1\}, \quad \alpha_{1,t}^{\max} = \frac{\mathrm{ERoEI}_{1,t}}{\Delta_{1,t} R_{1,t}} \left(\frac{1}{\sigma_t} E_t - \frac{1}{\mathrm{ERoEI}_{1,t}} R_{1,t} \right) \tag{3.26}$$

In the simulations reported in this section, we consider the simple, constant over time growth scenario:

$$\forall t \in \{0, \ldots, T-1\}, \quad \alpha_{1,t} = \alpha_0 = 0.1 \tag{3.27}$$

Observe that, in practice, the growth scenario may be constrained by the availability of resources for building capacities, as well as the availability of suitable locations to install capacities (sunny places in the case of photovoltaic panels).

3.4.3 Depletion of Nonrenewable Resources Scenario

We consider several scenarios for the depletion of nonrenewable resources. We arbitrarily define four scenarios and provide below the corresponding values of the parameters of the Hubbert curve:

– Peak at time 0:

$$t_0 = 0, \quad \tau = 30 \tag{3.28}$$

– Plateau at time 0:

$$t_0 = 0, \quad \tau = 60 \tag{3.29}$$

– Peak at time $t = 20$ years:

$$t_0 = 20, \quad \tau = 30 \tag{3.30}$$

– Plateau at time $t = 20$ years:

$$t_0 = 20, \quad \tau = 60 \tag{3.31}$$

The graph of resulting Hubbert curves can be found later in the chapter (Figs. 3.3, 3.4, 3.5, and 3.6). Note that the terms "peak" and "plateau" have been chosen to illustrate the fact that "plateau" curves are flatter than "peak" curves.

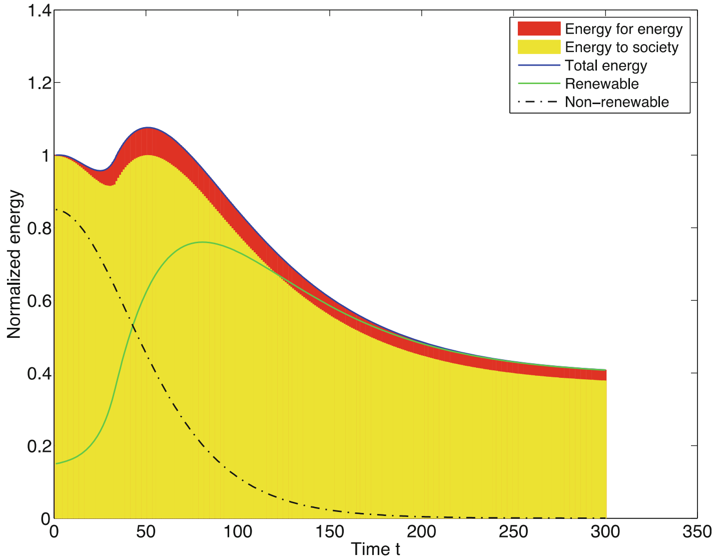

Fig. 3.3 Scenario peak at time $t = 0$

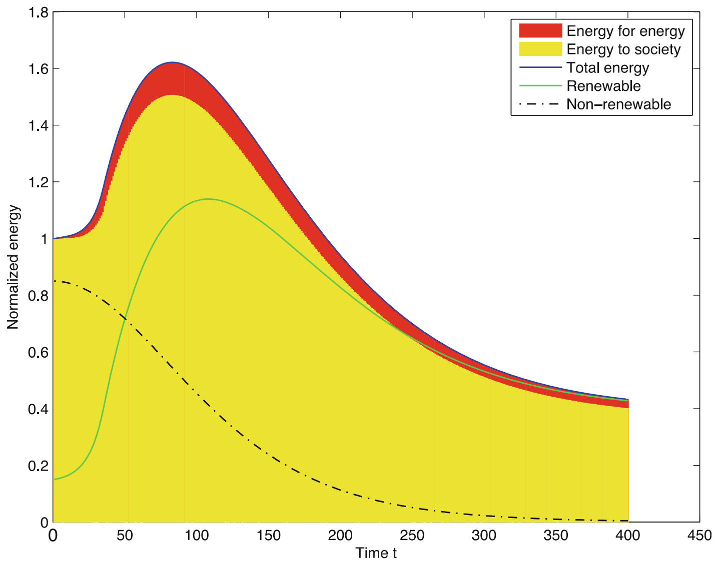

Fig. 3.4 Scenario plateau at time $t = 0$

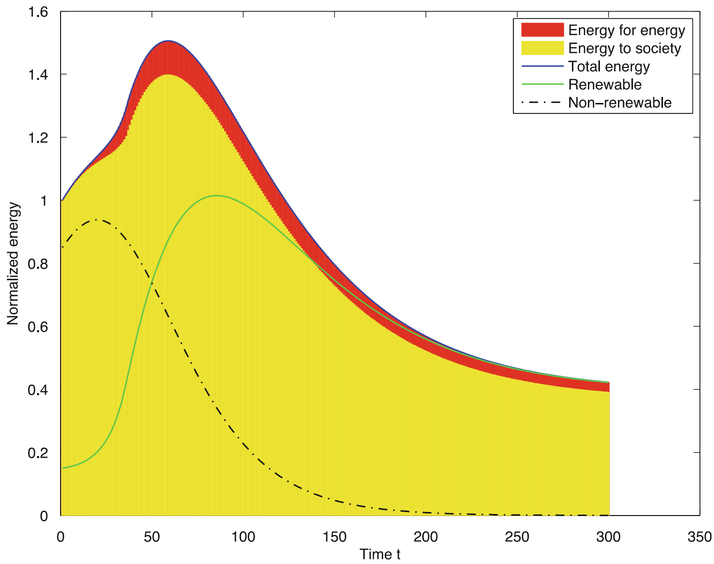

Fig. 3.5 Scenario peak at time $t = 20$

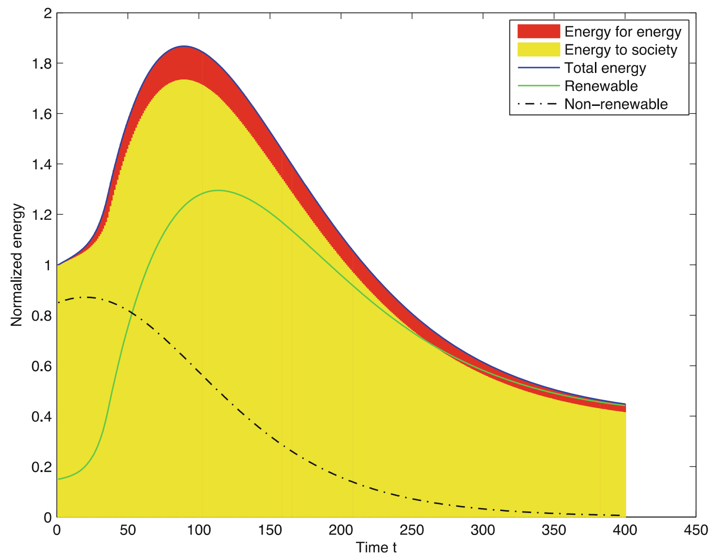

Fig. 3.6 Scenario plateau at time $t = 20$

3.4.4 Values of ERoEI and Lifetime

EROI for PV panels have been studied in the literature. For example in Lambert et al. (2012), a range of values varying from 6 to 12 is proposed, depending on the configurations. In the following experiments, we consider the average of these two values, i.e.,

$$\forall t \in \{0, \ldots, T-1\}, \quad \mathrm{ERoEI}_{1,t} = 9 \tag{3.32}$$

Note that (1) the computation of ERoEI values of PV panels is still discussed in the literature (Raugei et al. 2012), and that (2) it is very likely that such values will evolve significantly in the future. In all configurations considered in the following experiments, we consider a lifetime parameter equal to 20:

$$\forall t \in \{0, \ldots, T-1\}, \quad \Delta_{1,t} = 20 \tag{3.33}$$

3.4.5 Typical Runs

In this section, we provide simulation results obtained through our discrete-time models in the different configurations described above. Each graph shows, for every year, the evolution of the total energy (yearly) produced (top blue curve) which comprises two parts: energy dedicated to the production of energy ("energy for energy," red part) and energy dedicated to other needs of society ("energy to society," yellow part). We also report the levels of nonrenewable energy production (black dotted curve) and renewable energy production (green curve).

Note that the results presented in the following subsections should definitely not be considered as predictions. Their role is just to illustrate the behavior of the model in theoretical configurations.

Initially, it can be seen that the production of energy from renewable resources as well as the net energy to society both reached a global maximum before decreasing to a steady-state value. This decrease is a consequence of the "energy threshold" constraint: if the energy required for the long-term replacement of the current production capacity is larger than what the energy threshold constrain allows for investment, then the growth parameter becomes negative. In other words, the bubble that can be observed on the graphs illustrates the fact that the deployment of the renewable energy production capacities is boosted by the availability of nonrenewable resources.

As a second observation, we notice that the depletion scenario has an influence on the maximal level of production that can be reached during the transition phase. However, one can compute that it does not affect the steady-state production level, which is exactly the same in the four scenarios, and function of the ERoEI of the photovoltaic panels.

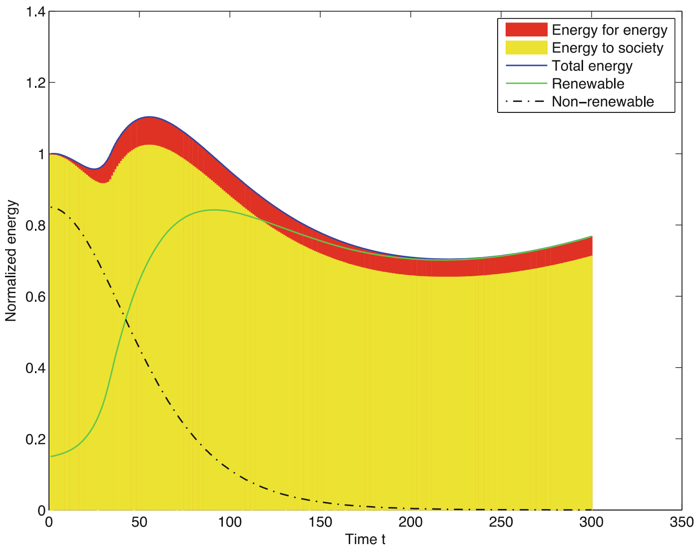

Fig. 3.7 Simulation result with an increase of the ERoEI parameter

To illustrate the influence of the ERoEI parameter on the levels of energy production, we give in Fig. 3.7 a last run of MODERN for which we consider a linear increase of the ERoEI parameter from 9 to 12 between time 0 and the time horizon (the growth scenario is the same as before, 10 % annual growth):

$$\forall t \in \{0, \ldots, T-1\}, \quad \text{ERoEI}_{1,t} = 9 + \frac{t}{T}(12-9) \tag{3.34}$$

3.5 On the Potential Benefits of Using Control Strategies

MODERN can be controlled through the growth scenario (which may be constrained by the system itself). This section discusses the potential benefits of using optimal control techniques for designing growth scenarios. In particular, we propose a control scheme that makes the variations of the net energy available to society vanish.

We have seen in Sect. 3.4 that growth scenarios may induce that the quantity of net energy available to society may reach a maximum level before decreasing to a steady-state level. We may assume that such a bubble effect can have destabilizing effects on society that one may want to avoid. It may thus be of interest to look for a sequence of growth parameters that would make such a "bubble" effect disappear. We illustrate below a sequence of growth that manages to do so.

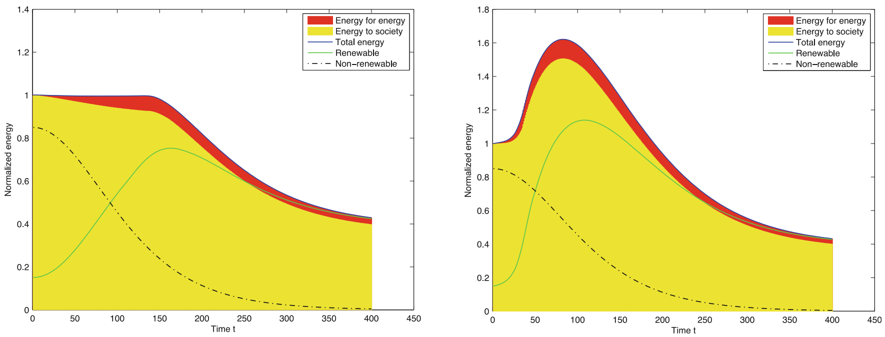

Fig. 3.8 Simulation results obtained when using the controlled growth (*left*) and a constant scenario growth (*right*)

We consider the "plateau at time $t = 0$" scenario, with a medium ERoEI of 9. We control the deployment growth using the following closed-loop growth scenario:

$$\forall t \in \{1, \ldots, T-1\}, \quad \alpha_{1,t} = \frac{B_{t-1} - B_t}{R_{1,t}} \tag{3.35}$$

This controller has been designed by considering the depletion of nonrenewable energy between two subsequent time steps and planning a growth that may counterbalance the depletion. We compare the result of this controlled growth scenario with the constant growth scenario obtained in the same depletion scenario (cf. Fig. 3.3):

It can be observed in Fig. 3.8 above that the simple controller proposed allows for the suppressing of the net energy bubble effect. One can also observe that negative growth parameters—which mean that the system is decreasing its renewable energy production capacities—appears around $t = 150$ in the controlled growth case, while it appears at around $t = 100$ in the noncontrolled case. In addition, one can see in Fig. 3.9 below that the cumulative sum of energy invested for the growth and long-term replacement of renewable energy production capacities is much smaller in the controlled growth scenario case.

We mention that, in the case of energy production technologies having a low ERoEI value, a strong growth can lead to a transient phenomenon called "energy cannibalism." This is a paradoxical situation where the energy invested for growing production capacities is so huge that the net energy available to society is temporarily decreasing while production capacities are increasing (Pearce 2009).

3.6 From Modelling to Society

Several articles in the literature relate to the link between societies' prosperity and their access to energy. Among others, historians, anthropologists, and economists have studied how energy has played a major role in the rise and decline of societies

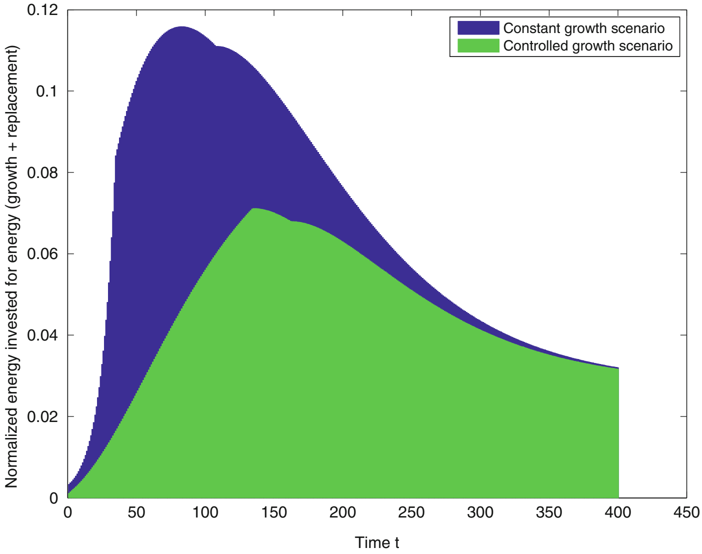

Fig. 3.9 Comparison of the quantities of energy invested for energy in the controlled growth scenario (*green*) and the constant growth scenario (*blue*)

(Meadows et al. 1972; Tainter 1988; Cleveland et al. 1984; Lambert et al. 2012; Jancovici 2011, 2013; Giraud and Kahraman 2014). The decline of the Western Roman Empire can be partly explained by (1) the decrease of agriculture efficiency (agriculture, which allows for the gathering of solar energy through photosynthesis, was the main energy source of the Roman Empire), and (2) the fact that looting was a nonrenewable way of obtaining access to resources (Tainter 1988). During the Middle Ages, the European GDP per inhabitant was increasing much faster than the Asiatic GDP during the period 1000–1500 (Maddison 2004). This has been explained by the increase of the use of windmills and sawmills in Western Europe, a mill being able to provide an energy equivalent to 40 men (Gimel 1976). This is even more striking in the case of the Dutch Golden Century, where the use of peat, as well as windmills and sawmills, allowed for increasing energy and food provision as well as better health, thus allowing cities to expand, boats to be built and trade developed (Zeeuw 1978). More recently, it has been shown that the impact on the GDP growth of capital accumulation and technical progress was minor compared to the role of energy in the period 1970–2012 (Giraud and Kahraman 2014) (see also Stern and Enflo 2013 for the specific case of Sweden). These three examples suggest that societies should consider energy as a key parameter of their economic development, and strategically manage their decisions related to energy supply.

The increasing use of energy over the last 150 years has generated an increase in work productivity that had never been seen before in the history of humanity. It is precisely this work productivity increase that has led to the diversification of human activities, resulting in complex societies with beneficial healthcare systems and a rich cultural life (Lambert et al. 2012; Jancovici 2013). In this study, we have used an energy threshold parameter, which basically models the fact that societies should not invest too much energy in producing energy otherwise the energy sector may cannibalize other human activities. We have observed that this parameter drastically constrains the model. As a consequence, technologies having a high ERoEI value lead to high renewable energy steady-state production levels. In this respect, we concur with several other papers stating that the ERoEI should be a major axis of technologies improvement. In parallel to this, a better geographical deployment strategy of renewable energy production technologies would result to an increase in their empirical ERoEI (Chatzivasileiadis et al. 2013, 2014).

The goal of this first version of MODERN (denoted by MODERN 1.0) was to model the deployment of renewable energy production capacities. In particular, MODERN 1.0 suggests that there is a possibility that the availability of nonrenewable energy in the short-term may create an artificial boost of energy production from nonrenewable resources that may not be sustainable on the long term, depending on the evolution of the technology. This potential effect should be taken into account when designing energy policies.

3.7 Conclusions

This chapter has introduced MODERN, a discrete-time formalization of the deployment of renewable energy production capacities. In particular, MODERN simulations show that deployment of renewable energy production capacities may be unsustainably boosted by the use of nonrenewable energy. This suggests that strategies for (1) deploying production capacities and (2) improving the efficiency of technologies, as well as the way they are used (energy efficiency) should be carefully designed.

MODERN 1.0 will be followed by other releases incorporating other parameters. In particular, MODERN 1.0 does not address the question of storage and fluctuations, which remains a major challenge of renewable energy deployment. Besides, MODERN 1.0 does not take into account the distinction between energy vectors (such as electricity, liquid fuels, heat...), which is another crucial point of the energy transition challenge. It would also be interesting to develop a version of MODERN, where the deployment of production capacities could be localized. This would enable the incorporation of constraints induced by local factors (geography, climate). However, besides calibration issues, more sophisticated versions of MODERN, taking into account such parameters, would come with a substantial increase in the level of difficulty for extracting near-optimal policies.

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