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Levelling the playing field: On the missing role of network externality in designing renewable energy technology deployment policies

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Keywords:
Renewable energy deployment; energy technology adoption; network externality; climate technology policies

JEL Classification:
Q41, Q42, Q48, Q54, Q55, Q58, H23, O13

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Levelling the playing field: On the missing role of network externality in designing renewable energy technology deployment policies

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1. Introduction

To address the combined challenges of increasing energy security, mitigating climate change, and reducing exposure to rising fuel prices, policymakers have demonstrated growing expectations on boosting technological innovation in energy sectors, particularly with respect to promoting a rapid and sustained deployment of renewable energy technology (RET) (Popp et al. 2009; Henderson and Newell, 2010; Gallagher et al., 2006, 2012; IEA, 2014a,b).[1] To design relevant policy schemes for RET deployment, the traditional well-established wisdom basically centres on bridging the cost gap of using high-cost RET versus low-cost fossil energy technology (FET), as RET is still not cost-efficient enough to compete with FET primarily due to the market failure to internalize the environmental costs associated with environment-polluting FET. Without a specific policy mechanism established to raise the costs of using FET or equivalently lower the costs of applying RET, environment-friendly yet high-cost RET would find it struggling in energy market adoption and deployment (Neuhoff, 2005; Foxon and Pearson, 2007, 2008; Henderson and Newell, 2010; Newell, 2010, 2011). [2]

Within such a traditional paradigm for RET deployment, various price-based policy instruments have been put in place that serve to eliminate the cost gap of RET versus FET, commonly through subsidizing the use of low-carbon RET or taxing the use of carbon-intensive FET (Menanteau et al., 2003; Madlener and Stagl, 2005; Fouquet and Johansson, 2008; Jacobsson et al., 2009; IEA, 2014a,b).[3] It has to be acknowledged that policy instruments oriented toward the removal of cost gap are superior policy approaches for their ability to provide financial "carrots" for RET developers that is not currently cost-efficient enough to compete with FET incumbents, thus leveraging private incentives to develop and deploy RET. By bridging the cost gap of using RET versus FET, a level playing field may be established in the demand side that favours RET adoption, thus creating demands for RET that otherwise would not exist at desired levels under current non-regulated market conditions (Menanteau et al., 2003; Madlener and Stagl, 2005; Jacobsson et al., 2009; IEA, 2014a,b).

However, this traditional paradigm of RET deployment policy is not a panacea, which may not

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[1] There is also a growing consensus that RET deployment policies serve as a useful complement to the emissions pricing policy like a cap-and-trade or tax system, in the sense that technology policies tend to lower the allowance price associated with achieving a given aggregate cap level or increase the total amount of emissions reductions achieved by a given tax (Jaffe et al, 2005; Newell, 2010).

[2] In addition to the non-regulated market that fails to internalize the environmental externality, the other factor that leads to the cost disadvantages of the newly emerging RET versus FET is that the incumbent FET has already experienced technical improvement and cost reductions for a long period of time (several decades or even centuries) prior to the commercialization of RET (Fouquet and Pearson, 2012; Pearson and Foxon, 2012; Grubler, 2012).

[3] More explicitly, existing energy policy for RET deployment has mostly relied upon financial subsidies, and production tax credits to drive down the cost of installation and use of RET, thus providing private incentive to generate electricity from renewable sources.

suffice by itself to usher in a technological transition to a desired RET-oriented energy future. While the conventional policy scheme based on the elimination of cost gap can appropriately correct for the environmental externality associated with both distinct types of energy technologies, a characteristic looseness inherent in the traditional policy paradigm is that it neglects the potential importance of network externality that often occurs in energy markets. In fact, in addition to the cost disadvantage versus incumbent FET,[4] the other significant barriers commonly encountered by the emerging RET upon commercialization concerns the network externality in energy markets (Islas, 1997; Unruh, 2000, 2002; Unruh and Carrillo-Hermosilla, 2006; Shum and Watanabe, 2010). In general, the network externality is referred to as an effect that occurs when the payoffs a user derives from the use of a good/service depend upon the number of other users already using the same good or service (Arthur, 1989; Liebowitz and Margolis, 1994, 1995a,b). In this regard, energy technologies are subject to the network externality on the ground that the payoffs derived by an agent from using a particular type of energy technology are related to the size of energy generation, distribution, and service network specific to that technology, which in turn are positively related to the number of other agents already adopting that energy technology within the same network.[5]

Accordingly, as the incumbent FET – the first commercially available energy technology - has accumulated its installed base and pervasive deployment within the pre-existing large-scale energy production and distribution network, such a strong dependence would create a network externality mechanism that makes it difficult to dislodge the dominant FET-based technological regime, leading to an inertia against the emerging RET (Arthur, 1989; Cowan, 1990; Cowan and Hulten, 1996).[6] As a result, the newly invented RET, once commercially available for market use, would face considerable

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[4] The short-run cost disadvantage encountered by RET may also exist in the long run, as innovation in both energy technologies can improve technical efficiency and reduce costs at a similar rate over time. For instance, the unconventional gas revolution has ripple effect on the entire fossil energy system, and has dramatically driven down the cost of using fossil energy.

[5] There are several reasons. First, a larger production network can harness the economies of scale to produce more quality secondary energy using a given amount of primary energy input. Second, a larger distribution network can gain more efficiency in delivering energy goods, allowing household to gain convenient and stable access to energy use terminals. Third, a large service network facilitates repair, maintenance, facility update, and other post-purchase service. Finally, in a decentralized energy market with a large number of participants, an energy system with a larger network is more robust to exist and operate, which facilitates interaction and trading among generators. For example, once a household has installed a solar rooftop system, the other households connected to the same grid would also like to follow, thus triggering a network effect (Shum and Watanabe, 2009, 2010).

[6] In particular, it is acknowledged that the electricity sector has become locked into centralized, large FET-based systems that dominate human, financial and institutional resources, which creates intense inertia to change. Furthermore, the decentralized RET-based technology may not be compatible with the characteristics of the existing system and are often handicapped in market access and competition because it serves as a threat to the established FET-based energy regime.

obstacles for large-scale deployment in energy markets, even if policy regulations have been put in place to eliminate RET's cost disadvantage (Islas, 1997; Unruh, 2000, 2002). Take a concrete example, even if China has launched initiatives to deploy the promising RET on a large scale, this largest energy consuming country that specialized in energy-intensive manufacturing still has a large stock of old and inefficient vintages of FET-based power plants that have expanded their installed base with an expected lifetime of several decades. As a result, not only does this lead to skyrocketing fossil energy uses in the short run, this FET-based installed network also comes with a formidable long-term carbon lock-in inertia in energy system that merits additional policy regulation beyond traditional price-based instruments like carbon pricing (Unruh and Carrillo-Hermosilla, 2006; Kalkuhl, 2012; Karlsson, 2012; Nordensvärd and Urban, 2015).

Therefore, to create a level playing field that facilitates RET deployment, the conventional policy regimes based on the removal of cost gaps may not suffice. In this context, this paper is intended to explore the missing role of energy network externality in the policy design for RET deployment, based on a model of energy technology adoption that features network externality. In particular, we aim to address two fundamental issues: why traditional regulatory regimes for RET deployment are not sufficient to induce private incentive to adopt RET? And which factors related to the network externality should be taken into account in designing a new policy framework for RET deployment?

To our knowledge, the existing literature has seminal research efforts investigating the general issue of technology adoption in the presence of network externality. For examples, Arthur (1989) showed how an inferior technology that by chance gains an early lead in adoption may eventually lock out other potential technologies due to the presence of network externality and path dependency. In a series of articles, Liebowitz and Margolis (1994, 1995a,b) discussed the classification of different forms of path-dependency as well as their implications regarding market efficiency and welfares. Katz and Shapiro (1985) developed a simple static model of oligopoly to assess the private and social incentives to achieve technical compatibility in the presence of consumption network externalities. Katz and Shapiro (1986) examined the dynamics of industry evolution in a market with technological change where there are two incompatible technologies subject to network externalities. Choi and Thum (1998) explored how the intergenerational interdependency induced by network externalities influences the pattern of technology adoption under various market structures. Farrell and Saloner (1985, 1986) analyzed the private and social incentives for the adoption of a new technology that is incompatible with the installed base.[7] Note that, while these classic works have a

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[7] The empirical studies on network externality and technology adoption include, for example, Gandal (1995), Brynjolfsson and Kemerer (1996), and Gowrisankaran and Stavins (2004).

virtue of laying the foundation for further studies in the field of network externality, the limitation is that an elaboration of network externality in the specific context of energy technology innovation is somewhat lacking.

Meanwhile, in the field of energy economics and policies, there is a growing body of literature having discussed the issue of energy technology innovation from the perspective of lock-in and network externality, with some policy prescriptions on addressing network externality for RET deployment (e.g., Unruh, 2000, 2002; van der Vleuten and Raven, 2006; del Rio and Unruh, 2007; Shum and Watanabe, 2009, 2010; Vergragt et al., 2011; Karlsson, 2012; Nordensvärd and Urban, 2015).[8] However, a frustrating aspect is that all these policy studies lack a rigorous exposition of the economics of network externality mechanism that shapes energy technological innovation and adoption.

To fill this gap, this paper contributes to a rigorous economic analysis on the issue of RET deployment in the presence of network externality, particularly with respect to the potential role of network externality in the policy design for RET deployment. By doing that, we hope to stimulate more economics-oriented efforts in future research, both theoretically and empirically, to explore the issue of RET innovation and deployment from the standpoint of energy network externality.[9]

The rest of this paper is organized as follows. Section 2 presents a model of energy technology adoption in the presence of network externality. Section 3 examines the incentive of private agents to adopt energy technologies. Section 4 provides a reformulated policy paradigm for RET deployment. Section 5 concludes.

2. A model of energy technology adoption with network externality

Given that the emerging RET with a higher cost of use is not cost-efficient enough to compete with

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[8] More explicitly, Karlsson (2012) discussed the problem of carbon lock-in in China at the limits of statism. Vergragt et al., (2011) assessed the lock-in reinforcement effect of adding carbon capture and storage to the fossil fuel socio-technical regime. van der Vleuten and Raven (2006) analyzed the lock-in and change on centralized electricity supply in Denmark. del Rio and Unruh (2007) applied an evolutionary economics framework to analyze the factors leading to lock-out of wind and solar photovoltaics in Spain. Shum and Watanabe (2009, 2010) discussed an innovation management approach for renewable energy deployment from the perspective of network externality and lock-in. Nordensvärd and Urban (2015) examined the specific low carbon policy such as feed-in tariff for wind energy in Germany can partly be a barrier to a comprehensive energy transition.

[9] As an exception, the theoretical work by Kalkuhl (2012) examined a mechanism of the lock-in into an inferior incumbent technology that dominates energy markets, at the expense of superior competing energy technology. However, the mechanism of carbon lock-in explored in this work is related to imperfection in innovation process and the competition between energy technologies, not capturing the lock in resulting from energy network externality.

low-cost FET incumbents, the traditional policy scheme for RET deployment is typically designed to bridge the cost gap of RET versus FET. Then a critical question arises: is this traditional regulatory regime sufficient to stimulate RET adoption? This section is intended to examine this issue based on a simple model of energy technology adoption that features network externality.

Consider that in the energy market there exist two distinct types of technologies that generate end-use energy goods/services, say, electric utility. One is FET that uses traditional carbon-intensive fossil primary energy like coal, oil, and gas, and it constitutes the incumbent energy technology that currently dominates energy production, distribution and service system. The other is RET that uses low-carbon primary energy like solar, wind, or biomass, and this new emerging technology becomes recently available for potential deployment in energy markets.[10]

To describe the network externality in energy markets, we consider an infinite-horizon economy with continuous time and admits a linear growth of household, i.e., for every period the economy has a number of n additional new households who enter energy markets sequentially and adopt energy technologies for accessing energy use (i.e., electric utility) as the basic living necessities. Hence, the size of the households adopting a particular type of energy technology would create an equivalent size of that corresponding energy technology network that is given by

$$N(t)=\int_0^t n\cdot ds = n\cdot t \quad ,$$

where it is suggested that at each point in time $t\in[0,\infty)$ there are n new households who enter energy markets and adopt a particular type of energy technology, thus expanding the size of energy generation, distribution and service network specific to that energy technology.

For the household's payoffs from using a particular type of energy technology, we consider that the payoffs depend on the size of energy technology network, i.e., the total number of households connected to the same network for energy use. This is because the payoffs derived by a household from using an energy technology is positively related to generation, distribution, and service network specific to that energy technology, which in turn are related to the total number of household already using that energy technology within the same network. In this line, we build on the model of network externality developed by the seminal work of Kats and Shapiro (1985), and Farrell and Saloner (1986),

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[10] More specifically, RET considered in this paper is referred to as the decentralized distributed RET like solar, wind where large-scale market deployment and expansion potentially occurs as expected, not corresponding to the mature carbon-free energy technology like nuclear or hydropower which has already experienced considerable up-scaling and reached a saturation level of deployment.

and consider energy network externality in an intertemporal dynamic framework.[11] More explicitly, a household who joins energy markets at each point in time $T \in [0,\infty)$ and adopts a particular type of energy technology would receive intertemporal payoffs that take the form as,

$$V(T) = \int_T^\infty u(N(t)) \cdot \exp(-r(t-T)) \cdot dt = \int_T^\infty (v(N(t)) - p) \cdot \exp(-r(t-T)) \cdot dt \qquad (1)$$

where the instantaneous payoff u derived from using a particular type of energy technology is equal to household's willingness to pay (WTP) v minus the price charged for using that energy technology p. In particular, the valuation or WTP a household attaches to that particular technology depends on the network size of that energy technology which is in turn related to the total number of households connected to that technology network for energy use $N(t)$. This specification is due to the fact that a household can gain more benefits from an energy technology with a larger network of production, distribution, and service system, thus a higher level of valuation or WTP would be put on the use of that energy technology.[12] Accordingly, the valuation function $v(N(t))$ is taken to be an increasing function of $N(t)$, with $v'(N(t)) > 0$, and $\lim_{N(t)\to\infty} v'(N(t)) = 0$.

Fig. 1 shows the timing of energy technological evolution. As the first-mover incumbent energy technology, FET becomes available for adoption from the date of technology introduction T_{FET}^I, and the size of FET network continually grows until the date of technology maturity T_{FET}^M, where the superscript "*I*" and "*M*" corresponds to technology introduction and maturity, and the subscript "*FET*" to fossil energy technology. Meanwhile, RET is a newly invented technology on the horizon and would be available afterwards at some time T_{RET}^I, and the size of RET network grows until its maturity time T_{RET}^M where the subscript "*RET*" to renewable energy technology. Accordingly, the instantaneous payoffs from using FET and RET are written as piecewise functions respectively,

$$u(N(t)) = \begin{cases} a + \beta \cdot n \cdot (t - T_{FET}^I) - p_{FET} & \text{if } \ t \in [T_{FET}^I, T_{FET}^M] \\ a + \beta \cdot n \cdot (T_{FET}^M - T_{FET}^I) - p_{FET} & \text{if } \ t \in [T_{FET}^M, \infty) \end{cases}, \qquad (2)$$

and

---

[11] The analysis in this paper extends the Kats and Shapiro (1985) static model of network externality into a dynamic framework which incorporates a forward-looking household receiving intertemporal payoffs from using energy technology throughout the technology lifecycle, in this sense, the basic setup in our model is more closely related to the seminal work by Farrell and Saloner (1986).

[12] As mentioned previously, the additional benefits attributable to a larger size of energy network lies in three folds. A larger production network can harness the economies of scale to produce more quality energy goods. A larger distribution network can gain more efficiency in delivering energy goods with more convenient access to energy use terminals. A large service network facilitates repair, maintenance, facility update, and other post-purchase service.

$$u(N(t)) = \begin{cases} a + \beta \cdot n \cdot (t - T_{RET}^{I}) - p_{RET} & \text{if} \quad t \in [T_{RET}^{I}, T_{RET}^{M}] \\ a + \beta \cdot n \cdot (T_{RET}^{M} - T_{RET}^{I}) - p_{RET} & \text{if} \quad t \in [T_{RET}^{M}, \infty) \end{cases}, \tag{3}$$

where Eq. (2) suggests that the size of FET network grows from the introduction date T_{FET}^{I} up to the maturity date T_{FET}^{M}, and after that the FET network reaches a saturation size $n \cdot (T_{FET}^{M} - T_{FET}^{I})$. Eq. (3) describes that the size of RET network grows from its introduction date T_{RET}^{I} until the maturity date T_{RET}^{M}, with the network size reaching a saturation level $n \cdot (T_{RET}^{M} - T_{RET}^{I})$ after the maturity T_{RET}^{M}.

For the sake of model tractability, the instantaneous payoff function takes a linear form as the network size grows, i.e., $a + \beta \cdot N(t) = a + \beta \cdot n \cdot t$,[13] where $a > 0$ is the network-independent basic level of WTP that is irrespective of network size, $\beta \times N(t)$ is the additional network-generated WTP attached to an energy technology with a network size $N(t)$ at time t, and $\beta > 0$ is the marginal effect of network externality on the household's WTP. Fig. 2 illustrates the underlying intuition, the basic network-independent WTP corresponds to the household's WTP for the basic utility derived from energy use terminal (i.e., thermal energy for cooking, heating, lighting etc).[14] Beyond this network-independent basic utility directly received from end use, an energy technology system with a larger production, distribution, and service network that supports end use tends to provide households with more indirect utilities, thus households are willing to attach additional valuation for an energy technology with a larger network.[15] Eqs. (2)-(3) also suggest that the payoffs received from using a particular energy technology are increasing in the network size until the date of network maturity. After that, the payoffs reach a constant saturation level. This feature basically accords with the general pattern of technology evolution over a lifecycle. That is, at the initial stage when new technologies are introduced into markets, there is a large potential to grow and accumulate market application. This leads to a period of sustained growth of technology deployment in the marketplace with an expanding network size. At the end of lifecycle the new technologies are in widespread

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[13] As our model extends a static payoff specification into a dynamic framework with an intertemporal payoff, we thus consider a simple linear form for instantaneous payoff function, since no analytical solution of the model could be provided with a more general form.

[14] In particular, no matter the energy technology is the simple self-sufficient biomass (without the network) or coal-fired power plant (with a large and sophisticated generation and distribution network), the basic functions and utility are the same - the thermal energy derived from the terminal, which is irrespective of the network attributes associated with different types of energy technology.

[15] A larger energy network creates a higher level of indirect utilities through the following channels. First, a larger generation network can benefit from the economies of scale to generate more quality secondary energy using a given amount of primary energy. Second, a larger distribution network can gain more efficiency in delivering energy goods, allowing more convenient and stable access to energy use terminals. Third, a large service network is more robust to provide post-purchase service like repair, maintenance, and facility update etc.

deployment with the growth potential exhausted, thus leading to a saturated level of network size (Masini and Frankl, 2002; Lund, 2006; Jacobsson and Johnson, 2000; Rao and Kishore, 2009).

During the time period $[T_{FET}^I, T_{FET}^M]$ only the incumbent FET has been commercialized in energy markets for end use, and RET is still in its infancy at research labs. Hence, a household who joins the energy markets at time $T \in [T_{FET}^I, T_{FET}^M]$ would adopt incumbent FET and receive the intertemporal payoff flows over the time frame,[16]

$$\begin{aligned} V_{FET}(T) &= \int_T^{\infty} [a+\beta\cdot n\cdot(t-T_{FET}^I)-p_{FET}]\cdot\exp(-r(t-T))\cdot dt \\ &= \int_T^{T_{FET}^M} [a+\beta\cdot n\cdot(t-T_{FET}^I)-p_{FET}]\cdot\exp(-r(t-T))\cdot dt \\ &+ [a+\beta\cdot n\cdot(T_{FET}^M-T_{FET}^I)-p_{FET}]\cdot\int_{T_{FET}^M}^{\infty}\exp(-r(t-T))\cdot dt \\ &= \underbrace{\frac{a+\beta\cdot n\cdot(T-T_{FET}^I)-p_{FET}}{r}}_{Installed\ \ Network\ \ Base\ \ Externality} + \underbrace{\frac{\beta\cdot n}{r^2}\cdot[1-\exp(-r(T_{FET}^M-T))]}_{Potential\ \ Network\ \ Growth\ \ Externality} \end{aligned} , \tag{4}$$

where the second line rewrites the payoffs $V_{FET}(T)$ as a sum of two parts: 1) Payoff streams from household entry date T to FET maturity date T_{FET}^M during which the size of FET network $N(t)$ expands linearly with time; and 2) payoff streams from FET maturity date T_{FET}^M to an infinite future during which the size of FET network remains the saturation constant level $N(T_{FET}^M)$. The third line explicitly derives the payoffs from adopting FET at time $T \in [T_{FET}^I, T_{FET}^M]$, where the first term is the payoffs attributable to *installed network base externality*: at the household entry date $T \in [T_{FET}^I, T_{FET}^M]$, FET has established an installed network base with a size of $N(T) = n\cdot(T-T_{FET}^I)$. The second term denotes the payoffs attributable to *potential network growth externality*: at the household entry date $T \in [T_{FET}^I, T_{FET}^M]$, FET still has a technology growth potential with network size expanding from T to FET maturity date T_{FET}^M (for a graphic illustration of network externality, see Fig. 3).

As Fig. 2 shows, the emerging RET is brought into energy markets at date T_{RET}^I, and then the network size of RET continually grows up to its maturity date T_{RET}^M. Given this technology evolution of RET, a household entering energy markets at any point in time $T \in [T_{RET}^I, T_{RET}^M]$ would receive intertemporal payoffs from adopting RET,

---

[16] For the derivation of Eq. (4), see Appendix.

$$
\begin{aligned}
V_{RET}(T) &= \int_T^{\infty} [a+\beta\cdot n\cdot(t-T_{RET}^I)-p_{RET}]\cdot\exp(-r(t-T))\cdot dt \\
&= \int_T^{T_{RET}^M} [a+\beta\cdot n\cdot(t-T_{RET}^I)-p_{RET}]\cdot\exp(-r(t-T))\cdot dt \\
&\quad + [a+\beta\cdot n\cdot(T_{RET}^M-T_{RET}^I)-p_{RET}]\cdot\int_{T_{RET}^M}^{\infty}\exp(-r(t-T))\cdot dt \\
&= \underbrace{\frac{a+\beta\cdot n\cdot(T-T_{RET}^I)-p_{RET}}{r}}_{Installed\ \ Network\ \ Base\ \ Externality} + \underbrace{\frac{\beta\cdot n}{r^2}\cdot[1-\exp(-r(T_{RET}^M-T))]}_{Potential\ \ Network\ \ Growth\ \ Externality}
\end{aligned}
\quad , \qquad (5)
$$

where the second line rewrites the payoffs $V_{RET}(T)$ as a sum of two parts: 1) Payoff streams from household entry date T to RET maturity date T_{RET}^M during which the size of RET network $N(t)$ expands linearly with time; 2) payoff streams from RET maturity date T_{RET}^M to an infinite future during which the size of RET network remain at the saturation level $N(T_{RET}^M)$. The third line obtains the explicit form of the payoffs from adopting RET at time $T\in[T_{RET}^I, T_{RET}^M]$, where the first term is the payoffs attributable to *installed network base externality*: at the date of household entry $T\in[T_{RET}^I, T_{RET}^M]$, RET has established an installed network base with a size of $N(T)=n\cdot(T-T_{RET}^I)$. The second term denotes the payoffs attributable to *potential network growth externality*: at the household entry date $T\in[T_{RET}^I, T_{RET}^M]$, RET still has a technology growth potential with its network size expanding from T up to the RET's maturity date T_{RET}^M.

To summarize, the payoffs received by a household who joins energy markets and then adopts FET at each point in time $T\in[T_{FET}^I,\infty)$ is given by

$$
V_{FET}(T) = \begin{cases}
\underbrace{\frac{a+\beta\cdot n\cdot(T-T_{FET}^I)-p_{FET}}{r}}_{Installed\ \ Network\ \ Base\ \ Externality} + \underbrace{\frac{\beta\cdot n}{r^2}\cdot[1-\exp(-r(T_{FET}^M-T))]}_{Potential\ \ Network\ \ Growth\ \ Externality} & \text{if} \quad T\in[T_{FET}^I, T_{FET}^M] \\
\underbrace{\frac{a+\beta\cdot n\cdot(T_{FET}^M-T_{FET}^I)-p_{FET}}{r}}_{Installed\ \ Network\ \ Base\ \ Externality} & \text{if} \quad T\in[T_{FET}^M,\infty)
\end{cases}
, (6)
$$

and the payoffs received by a household who joins energy markets and chooses to adopt RET at any point in time $T\in[T_{RET}^I,\infty)$ takes the form as

$$
V_{RET}(T) = \begin{cases}
\underbrace{\frac{a+\beta\cdot n\cdot(T-T_{RET}^I)-p_{RET}}{r}}_{Installed\ \ Network\ \ Base\ \ Externality} + \underbrace{\frac{\beta\cdot n}{r^2}\cdot[1-\exp(-r(T_{RET}^M-T))]}_{Potential\ \ Network\ \ Growth\ \ Externality} & \text{if} \quad T\in[T_{RET}^I, T_{RET}^M] \\
\underbrace{\frac{a+\beta\cdot n\cdot(T_{RET}^M-T_{RET}^I)-p_{RET}}{r}}_{Installed\ \ Network\ \ Base\ \ Externality} & \text{if} \quad T\in[T_{RET}^M,\infty)
\end{cases}
. (7)
$$

The temporal profiles of the payoffs from adopting FET and RET over the time horizon $T\in[0,\infty)$

are displayed in Fig. 4. The red solid line corresponds to the payoffs from using FET $V_{FET}(T)$, which consists of a sum of payoffs attributable to installed network base effect $V_{FET}^{NBE}(T)$ and potential network growth effect $V_{FET}^{NGE}(T)$, i.e., $V_{FET}(T)=V_{FET}^{NBE}(T)+V_{FET}^{NGE}(T)$. The red dash line corresponds to the payoffs attributable to installed network base effect $V_{FET}^{NBE}(T)$, and the gap between red solid and dash lines corresponds to the payoffs attributable to potential network growth effect $V_{FET}^{NGE}(T)$. Similarly, the blue solid line illustrates the temporal profiles of the payoffs from using the newly emerging RET $V_{RET}(T)$, and the blue dash line corresponds to the payoffs attributable to installed network base effect $V_{RET}^{NBE}(T)$, with the gap between blue solid and dash lines denoting the payoffs attributable to potential network growth effect $V_{RET}^{NGE}(T)$.

There are several features. First, at the date $T = T_{FET}^{I}$ when FET is just introduced in markets, there is the largest potential for FET to grow and accumulate its market base. Hence, the payoffs generated by potential network growth effect reach the highest level, creating the largest gap between red solid and dash lines. Second, as time proceeds over the period $T \in (T_{FET}^{I}, T_{FET}^{M})$, FET continues to accumulate and expand its network base. As a result, the payoffs attributable to the installed network base effect $V_{FET}^{NBE}(T)$ increase, and the payoffs generated by potential network growth effect $V_{FET}^{NGE}(T)$ decline, which is shown by the shrinking gap between red solid and dash lines. Finally, once the date of FET maturity is reached $\forall T \in [T_{FET}^{M}, \infty)$, the network of FET becomes saturated, without further network expansion. As a result, the payoffs attributable to potential network growth effect fall off with time and disappear $V_{FET}^{NGE}(T)=0$, leaving only the payoffs attributable to installed network base effect $V_{FET}^{NBE}(T)$ in the composition of the total payoffs, , i.e., $V_{FET}(T)=V_{FET}^{NBE}(T),\ \ \forall T \in [T_{FET}^{M}, \infty)$. Hence, both red solid and dash lines converge once the date of FET maturity is reached. [17]

3. Non-adoption of renewable energy technology

Based on Eqs. (6)-(7) with the specification of the payoffs received from adopting FET and RET in the presence of network externality, we then obtain the following results that characterize the temporal profiles of payoffs from adopting both types of energy technologies.

Lemma 1 *In the above-described model of RET adoption in the presence of energy network externality, consider that FET is available in energy markets at the date of technology introduction* T_{FET}^{I} *and expands its network size until the date of technology maturity* T_{FET}^{M}*, then the payoffs received by a household who adopts FET at the date of technology maturity* T_{FET}^{M} *are larger than those received at any point in time before FET*

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[17] The temporal profile of the newly emerging RET also shows these similar features.

maturity date $T \in [T_{FET}^{I}, T_{FET}^{M})$*, i.e.,* $V_{FET}(T_{FET}^{M}) > V_{FET}(T)$ *holds for* $\forall T \in [T_{FET}^{I}, T_{FET}^{M})$*. Moreover, given that RET is available in energy markets at some point in time* T_{RET}^{I}*, and the size of RET network grows up to its maturity date* T_{RET}^{M}*, then the payoffs received by a household who adopts RET at RET introduction date* T_{RET}^{I} *are smaller than those received at any point in time after RET is introduced* $\forall T \in (T_{RET}^{I}, \infty)$*, i.e.,* $V_{RET}(T_{RET}^{I}) < V_{RET}(T)$ *holds for* $\forall T \in (T_{RET}^{I}, \infty)$.

Proof. We examine the monotonic property of the payoffs function to prove this lemma. For the adoption of FET, differentiating the corresponding payoff function Eq. (6) with respect to the argument T obtains,

$$V_{FET}'(T) = \frac{dV_{FET}(T)}{dT} = \frac{\beta \cdot n}{r}[1 - \exp(-r(T_{FET}^{M} - T))] > 0 \qquad .$$

Consider that at any point in time $\forall T \in [T_{FET}^{I}, T_{FET}^{M})$, the term is positive $T_{FET}^{M} - T > 0$, and the payoff Eq. (6) is an increasing function with its argument $V_{FET}'(T) > 0$, so $V_{FET}(T_{FET}^{M}) > V_{FET}(T)$ always holds for $\forall T \in [T_{FET}^{I}, T_{FET}^{M})$. The same proof applies to adoption of RET, differentiating the corresponding payoff function Eq. (7) with respect to the argument T obtains

$$V_{RET}'(T) = \frac{dV_{RET}(T)}{dT} = \frac{\beta \cdot n}{r}[1 - \exp(-r(T_{RET}^{M} - T))] > 0 \qquad .$$

Consider that at any point in time $\forall T \in (T_{RET}^{I}, T_{RET}^{M})$, the term is positive $T_{RET}^{M} - T > 0$, and the payoff Eq. (7) is an increasing function with its argument $V_{RET}'(T) > 0$, so $V_{RET}(T) > V_{RET}(T_{RET}^{I})$ always holds for $\forall T \in (T_{RET}^{I}, T_{RET}^{M})$. Furthermore, the payoffs would remain constant once the date of technology maturity is reached, i.e., $V_{RET}(T) = V_{RET}(T_{RET}^{M})$ for $\forall T \in [T_{RET}^{M}, \infty)$. Combing both time intervals, we obtain $V_{RET}(T_{RET}^{I}) < V_{RET}(T)$ holds for $\forall T \in (T_{RET}^{I}, \infty)$. ■

As shown by the red sold line in Fig. 4, the economic intuitions associated with Lemma 1 are straightforward. Starting from the lowest level at the date of technology introduction, the payoffs from adopting a particular energy technology would trend up with time over the network expansion period and reach the highest level at the maturity date. Intuitively, as a technology lifecycle evolves into the maturity stage, the potential network growth effects have all been realized and transformed into the existing installed network base effects, thus accumulating the largest network size to deliver network-related payoffs to the household. By contrast, when a household adopts a particular energy technology at the time when it just becomes available in niche markets, the potential network growth effects have not yet been transformed into installed network base effects, thus building a network with the smallest size to deliver network-related payoffs. Based on Lemma 1, we obtain the following proposition that characterizes an outcome in which the household has no incentive to adopt RET

Proposition 1 *In the above-described model of RET adoption in the presence of energy network externality, consider that RET is a newly emerging technology that becomes available in energy market after the incumbent FET matures, i.e.,* $T_{RET}^{I} > T_{FET}^{M}$*, then the installed network base externality in favour of FET incumbent would lead to an outcome that the household has no incentive to adopt RET when this emerging technology becomes available for use at time* T_{RET}^{I}*.*

Proof. To prove that a household has no incentive to adopt RET at the date of RET introduction T_{RET}^{I}, we need to establish that the payoffs received from using RET is lower than those in the case of adopting FET, i.e., $V_{RET}(T_{RET}^{I}) < V_{FET}(T_{RET}^{I})$.

Given that RET is brought into energy markets after FET matures, i.e., $T_{RET}^{I} > T_{FET}^{M}$, the payoffs from using FET at time T_{RET}^{I} is the same as those at time T_{FET}^{M}, i.e., $V_{FET}(T_{RET}^{I}) = V_{FET}(T_{FET}^{M})$. Hence, the above-mentioned condition that is sufficient to the no-adoption of RET is equivalent to,

$$V_{RET}(T_{RET}^{I}) < V_{FET}(T_{RET}^{I}) \;\Rightarrow\; V_{RET}(T_{RET}^{I}) < V_{FET}(T_{FET}^{M}) \quad , \tag{8}$$

where the payoffs function take explicit forms as (c.f., Eqs. (4)-(5))

$$\begin{aligned} V_{RET}(T_{RET}^{I}) &= \frac{a - p_{RET}}{r} + \frac{\beta \cdot n}{r^2} \cdot [1 - \exp(-r(T_{RET}^{M} - T_{RET}^{I}))] \\ V_{FET}(T_{FET}^{M}) &= \frac{a + \beta \cdot n \cdot (T_{FET}^{M} - T_{FET}^{I}) - p_{FET}}{r} \end{aligned} \quad , \tag{9}$$

substituting Eq. (9) into Eq. (8), the condition of no-adoption of RET thus boils down to

$$\begin{aligned} & V_{RET}(T_{RET}^{I}) - V_{FET}(T_{FET}^{M}) \\ & = \frac{p_{FET} - p_{RET}}{r} + \frac{\beta \cdot n}{r} \cdot \left[\frac{1 - \exp(-r(T_{RET}^{M} - T_{RET}^{I}))}{r} - (T_{FET}^{M} - T_{FET}^{I}) \right] < 0 \end{aligned} \quad , \tag{10}$$

where the first term on the right-hand side is negative due to the fact that the cost of using FET is generally lower than that of using RET, i.e., $p_{FET} < p_{RET}$. Furthermore, for simplicity we consider that both FET and RET have the same period of technology lifecycle from technology introduction to maturity $T_{FET}^{M} - T_{FET}^{I} = T_{RET}^{M} - T_{RET}^{I}$, we thus have

$$\begin{aligned} & \frac{1 - \exp(-r(T_{RET}^{M} - T_{RET}^{I}))}{r} - (T_{FET}^{M} - T_{FET}^{I}) = \frac{1 - \exp(-r \cdot (T_{FET}^{M} - T_{FET}^{I}))}{r} - (T_{FET}^{M} - T_{FET}^{I}) < 0 \\ & \Leftrightarrow \; 1 - \exp(-r \cdot (T_{FET}^{M} - T_{FET}^{I})) < r \cdot (T_{FET}^{M} - T_{FET}^{I}) \end{aligned} ,$$

which holds for all positive values of the discount factor r, thus Eq. (10) is always negative. ■

Proposition 1 suggests that a significant barrier faced by RET upon introduction in markets is concerned with the network externality. At the time when the emerging RET becomes available to commercial use, the incumbent FET has accumulated a network advantage by having transforming potential network growth effect into installed network base effect that generates network-generated payoffs from FET adoption. As a result, a household who joins energy market at that time has no incentive to adopt RET. This mechanism is illustrated in Fig. 4, at the date of RET introduction, the red line (payoffs from using FET) is well above the blue line (payoffs from using RET). In addition, we further argue that the non-adoption of RET is actually the household's payoffs-improving choice at each point in time after the date of RET introduction, which is summarized in the following result.

Corollary 1 *In the above-described model of RET adoption in the presence of energy network externality, consider that RET is a newly emerging technology that becomes available for household use after the incumbent FET matures, i.e.,* $T_{RET}^{I} > T_{FET}^{M}$, *then the installed network base externality in favour of FET leads to the non-adoption of RET at any point in time after RET is available in energy markets* $\forall T \in [T_{RET}^{I}, \infty)$.

Proof. To prove that a household has no incentive to adopt RET at any point in time $T \in [T_{RET}^{I}, \infty)$, we need to establish that the payoffs received from using RET is lower than those from adopting FET, i.e., $V_{RET}(T) < V_{FET}(T)$, for $\forall T \in [T_{RET}^{I}, \infty)$. We examine these conditions for two separate time sub-intervals $[T_{RET}^{I}, T_{RET}^{M})$ and $[T_{RET}^{M}, \infty)$. First, for the sub-interval $\forall T \in [T_{RET}^{I}, T_{RET}^{M})$, given that RET becomes available in energy markets after FET matures, i.e., $T_{RET}^{I} > T_{FET}^{M}$, the payoffs from using FET at each point in time $\forall T \in [T_{RET}^{I}, T_{RET}^{M})$ are the same as those received at the date of FET maturity T_{FET}^{M}, i.e., $V_{FET}(T) = V_{FET}(T_{FET}^{M})$. Accordingly, the above-mentioned condition that is sufficient to the non-adoption of RET is equivalent to,

$$V_{RET}(T) < V_{FET}(T) \quad \Rightarrow \quad V_{RET}(T) < V_{FET}(T_{FET}^{M}) \quad , \tag{11}$$

where

$$\begin{aligned} V_{RET}(T) &= \frac{a+\beta\cdot n\cdot(T-T_{RET}^{I})-p_{RET}}{r}+\frac{\beta\cdot n}{r^{2}}\cdot[1-\exp(-r(T_{RET}^{M}-T))] \\ V_{FET}(T_{FET}^{M}) &= \frac{a+\beta\cdot n\cdot(T_{FET}^{M}-T_{FET}^{I})-p_{FET}}{r} \end{aligned} ,$$

and the condition of no-adoption of RET Eq. (11) boils down to

$$\begin{aligned} &V_{RET}(T)-V_{FET}(T_{FET}^{M}) \\ &=\frac{p_{FET}-p_{RET}}{r}+\frac{\beta\cdot n}{r}\left[\frac{1-\exp(-r(T_{RET}^{M}-T))}{r}+T-T_{RET}^{I}-(T_{FET}^{M}-T_{FET}^{I})\right] \\ &=\frac{p_{FET}-p_{RET}}{r}+\frac{\beta\cdot n}{r}\left[\frac{1-\exp(-r(T_{RET}^{M}-T))}{r}+T-T_{RET}^{M}\right]<0 \end{aligned} \tag{12}$$

where the second line uses the fact that the cost of using FET is lower than that of using RET, i.e., $p_{FET} < p_{RET}$, and the last line considers that both FET and RET have the same growth period of lifecycle from technology introduction to maturity $T_{FET}^{M} - T_{FET}^{I} = T_{RET}^{M} - T_{RET}^{I}$. Accordingly, for all positive values of the discount factor r, Eq. (12) is negative $V_{RET}(T) - V_{FET}(T_{FET}^{M}) < 0$, for $\forall T \in [T_{RET}^{I}, T_{RET}^{M})$. Second, for the sub-interval of time after RET network matures $\forall T \in [T_{RET}^{M}, \infty)$, the payoffs received from adopting both RET and FET are given by,

$$\begin{aligned} V_{RET}(T) &= V_{RET}(T_{RET}^{M}) = \frac{a + \beta \cdot n \cdot (T_{RET}^{M} - T_{RET}^{I}) - p_{RET}}{r} \\ V_{FET}(T) &= V_{FET}(T_{RET}^{M}) = V_{FET}(T_{FET}^{M}) = \frac{a + \beta \cdot n \cdot (T_{FET}^{M} - T_{FET}^{I}) - p_{FET}}{r} \end{aligned} .$$

Given that $p_{FET} < p_{RET}$, and $T_{FET}^{M} - T_{FET}^{I} = T_{RET}^{M} - T_{RET}^{I}$, we have $V_{RET}(T) < V_{FET}(T)$ for $\forall T \in [T_{RET}^{M}, \infty)$. Combining with the results for two sub-interval $[T_{RET}^{I}, T_{RET}^{M})$ and $[T_{RET}^{M}, \infty)$, we thus obtains that $V_{RET}(T) < V_{FET}(T)$ for $\forall T \in [T_{RET}^{I}, \infty)$. ■

As illustrated in Fig. 4, the economic intuitions associated with Corollary 1 are straightforward. At each point in time after the date of RET introduction, the red line of FET (payoffs from using FET) is always above the red line (payoffs from using RET). Therefore, due to the installed network base externality in favour of FET, households have no incentive to adopt the newly emerging RET. Taken together, Proposition 1 and Corollary 1 suggest that the payoffs from adopting FET is larger than those from using RET at both the date of RET introduction and afterwards.

4. Policy regulations for renewable energy adoption

Given that the private agents have no incentive to adopt the newly emerging RET due to the presence of network externality, specific policy regulations are thus required to resolve the market failure attributable to network externality, which is summarized in the following result.

Proposition 2 *In the above-described model of RET adoption in the presence of energy network externality, given that the installed network base externality in favour of incumbent FET would lead to the non-adoption of RET when this new technology becomes available for household's use, the government can induce the adoption of RET through policy regulations that fully correct for both cost gap and network externality gap. In particular, the level of government policy regulation sufficient to induce RET adoption at any point in time after RET is available* $\forall T \in [T_{RET}^{I}, \infty)$ *is characterized by*

$$G = p_{RET} - p_{FET} + \beta \cdot n \cdot \left[T_{FET}^{M} - T_{FET}^{I} - (T - T_{RET}^{I}) - \frac{1-\exp(-r \cdot (T_{RET}^{M} - T))}{r} \right]. \qquad (13)$$

Moreover, as time proceeds towards RET maturity T_{RET}^{M}, *RET's potential network growth externality in favour of RET is fully realized, thus the level of policy regulation for RET deployment needs to phase out and eventually reaches a level just serving to eliminate the cost gap* p_{RET} - p_{FET}.

Proof. Suppose that the policy regulations, denoted by G, takes the form of a flow variable that is imposed annually throughout the time frame after RET becomes available $\forall T \in [T_{RET}^{I}, \infty)$, then the level of policy regulation required to eliminate RET's payoffs gap relative to RET and thus induce RET adoption is equal to

$$\int_{T}^{\infty} G \cdot \exp(-r(t-T)) \cdot dt = V_{FET}(T) - V_{RET}(T) \quad , \qquad (14)$$

where the payoffs function for using RET and FET at time $\forall T \in [T_{RET}^{I}, \infty)$ are

$$V_{RET}(T) = \frac{a + \beta \cdot n \cdot (T - T_{RET}^{I}) - p_{RET}}{r} + \frac{\beta \cdot n}{r^2} \cdot [1 - \exp(-r(T_{RET}^{M} - T))]$$

$$V_{FET}(T) = V_{FET}(T_{FET}^{M}) = \frac{a + \beta \cdot n \cdot (T_{FET}^{M} - T_{FET}^{I}) - p_{FET}}{r}$$

Substituting the payoff functions into Eq. (14) and rearranging obtains the policy regulation required for RET adoption as characterized in Eq. (13). Furthermore, the monotonicity shows that Eq. (13) is a decreasing function with its argument T, i.e., as T goes up, the required policy regulations fall and finally reach a regulation level based on an elimination of cost gap $p_{RET} - p_{FET}$. ■

As shown in Fig. 4, the intuitions that underline Proposition 2 are as follows. The gap between red and blue solid lines denotes the level of policy regulation sufficient to induce RET adoption at each point in time after RET becomes available. Notably, the gap reaches the highest level at the date of RET introduction, and then fall off with time as the RET network starts expansion. Once the RET network undergoes an equivalent network expansion until its maturity, the potential network growth externality would be fully transformed into the installed network base externality in favour of RET, thus facilitating RET adoption and the phase-out of policy regulation. In particular, it is also at this moment that the playing field is levelled for RET deployment, in the sense that only when RET and FET accumulate an equivalent size of installed networks and RET's payoffs gap attributable to network externality has been eliminated, traditional policy instruments based on the elimination of cost gap can take effect for RET deployment, and now the payoffs gap essentially reflects the cost gap resulting from environmental externality associated with both distinct types of energy technologies.

To elicit the policy implications of Proposition 2 for RET deployment, we consider a particular case by setting $T = T^{I}_{RET}$ in Eq. (13), from which we can characterize the level of policy regulation sufficient to induce RET adoption at the date of RET introduction as

$$\begin{aligned} G &= \underbrace{p_{RET} - p_{FET}}_{\cos t\ \ gap} + \underbrace{\beta \cdot n \cdot \left[T^{M}_{FET} - T^{I}_{FET} - \frac{1 - \exp(-r \cdot (T^{M}_{RET} - T^{I}_{RET}))}{r} \right]}_{network\ \ externality\ \ gap} \\ &= \underbrace{(p_{RET} - p_{FET})}_{(1)} + \underbrace{\beta \cdot n \cdot (T^{M}_{FET} - T^{I}_{FET})}_{(2)} - \underbrace{\beta \cdot n \cdot [1 - \exp(-r(T^{M}_{RET} - T^{I}_{RET}))] / r}_{(3)} \end{aligned} \quad . \tag{15}$$

where Eq. (15) can be thought of as a reformulation of RET deployment policy scheme, in particular, it is suggested that the traditional regime centring on the elimination of cost gap should be extended into a new one that corrects for both cost and network externality gap.

More explicitly, the first term in the right-hand side corresponds to the cost gap to be bridged, mainly reflecting the traditional wisdom in designing RET adoption policies. That is, conventional policy regulations focus on removing RET's cost disadvantage versus FET, either through raising the cost of FET by carbon taxation or lowering the cost of RET by renewable subsidies, particularly aimed at internalizing the environmental externality. However, this does not suffice to ensure a rapid and sustained deployment of RET, because it ignores the potential role of network externality. As shown by the second term that corresponds to FET's installed network base externality, when the emerging RET becomes available for adoption at time T^{I}_{RET}, the incumbent FET has accumulated an installed base network advantage over its growth period,

$$\int_{T^{I}_{FET}}^{T^{M}_{FET}} \beta \cdot n \cdot dt = \beta \cdot n \cdot (T^{M}_{FET} - T^{I}_{FET}) \quad . \tag{16}$$

Consider that the incumbent FET-based technological regime has taken a substantial period of time (several decades or centuries) to build network bases, the existing installed network base externality in favour of FET is thus substantially large, implying that the level of policy regulation required to induce RET adoption may largely outweigh that based on bridging cost gaps. Finally, the last term on the right-hand side corresponds to RET's potential network growth externality. That is, at the time when the emerging RET becomes available for use, a household who adopts RET is expected to receive an intertemporal payoff attributable to RET's potential network growth externality over the RET lifecycle $T^{M}_{FET} - T^{I}_{FET}$.

$$\int_{T^{I}_{RET}}^{T^{M}_{RET}} \beta \cdot n \cdot \exp(-r(t - T^{I}_{RET})) \cdot dt = \frac{\beta \cdot n \cdot [1 - \exp(-r(T^{M}_{RET} - T^{I}_{RET}))]}{r} \quad . \tag{17}$$

where there is discounting embedded in the streams of future payoffs due to the fact that RET's potential network growth effects have not been transformed into installed network base effects at the date of RET introduction, so discounting factor should be used to value future payoff streams that have not been fully realized at that time point. Furthermore, as a counter force to the above-described FET's installed network base externality, RET's potential network growth effect partially mitigates the inertia against RET adoption. Intuitively, as more RET-based generators and users are potentially connected within a network (e.g., small grid), other agents tend to have a higher incentive to join the same grid for the network-generated benefits (e.g., economies of scale, convenience to access energy use and post-purchase service), ushering self-propagation dynamics that accelerate RET deployment.

Taken together, the net effect of network externality associated with both types of energy technologies boils down to,

$$\beta \cdot n \cdot \left[T_{FET}^{M} - T_{FET}^{I} - \frac{1-\exp(-r \cdot (T_{RET}^{M} - T_{RET}^{I}))}{r} \right] > 0 \quad . \tag{18}$$

Given that FET and RET share the same period of network growth T_{RET}^{M} - T_{RET}^{I} = T_{FET}^{M} - T_{FET}^{I}, the installed network base externality in favour of incumbent FET would outweigh the potential network growth externality that favours newly created RET.[18] Intuitively, at the date of RET introduction, the first-mover incumbent FET has completed network expansion and maximized network size. As FET's potential network growth effects have all been fully realized and transformed into installed network base effects, the payoffs from using FET takes a form of an intertemporal summation of instantaneous payoff flows, without discounting (c.f., Eq. (16)). In contrast, at the date of RET introduction, this new emerging RET just embarks on network expansion, and its potential network growth has not been fully realized and transformed into installed network base, there is thus discounting embedded in the future payoff streams (c.f., Eq. (17)). As a result, even if both FET and RET share the same period of network growth, the installed network base externality in favour of incumbent FET would outweigh the potential network growth externality that favours newly created RET.

Therefore, given that the net effect of network externality favours incumbent FET and leads to an inertia against the emerging RET, traditional policy regulation based on eliminating cost gap may not be sufficient, and a new policy paradigm for RET deployment should consider extending the

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[18] Define $T_{RET}^{M} - T_{RET}^{I} = T_{FET}^{M} - T_{FET}^{I} = T$ as the period of technology network growth, the second term on the right-hand side of Eq. (18) boils down to $r \cdot T - 1 + \exp(-r \cdot T)$, taking differentiation with respect to T obtains $r \cdot (1-\exp(-r \cdot T)) > 0$ for $\forall T > 0$. Hence, the larger the network growth period T, the larger the net effect of network externality in favour of incumbent FET.

traditional scheme centring on eliminating cost gap to a new one that corrects for both cost and network externality gap,

$$G = \underbrace{p_{RET} - p_{FET}}_{\cos t\, gap} + \underbrace{\beta \cdot n \cdot \left[T^{M}_{FET} - T^{I}_{FET} - \frac{1 - \exp(-r \cdot (T^{M}_{RET} - T^{I}_{RET}))}{r} \right]}_{network\ \ externality\ \ gap} > p_{RET} - p_{FET} \,. \tag{19}$$

Taking a concrete example, suppose that FET and RET have the same 100-year growth period, i.e., T^{M}_{FET} - T^{I}_{FET} = T^{M}_{RET} - T^{I}_{RET} = 100. Using a discount rate $r = 5\%$ to discount cross-period utilities, we find that the payoffs gap attributable to network externality is equivalent to a gap in network growth over a period of 80 years.[19] Moreover, the annual inflows of household for energy use are positive $n > 0$. According to the empirical evidence provided by Gandal (1995), Brynjolfsson and Kemerer (1996), and Gowrisankaran and Stavins (2004), households' valuation of network externality is positive $\beta > 0$, suggesting that households attach additional WTP to a particular technology with a larger network size. Therefore, policy regulations for RET deployment are required to correct for RET's network externality gap versus incumbent FET.

Furthermore, consider that the policy regulations required for RET deployment are imposed on the two specific energy technologies (FET and RET) simultaneously and go into effect at the date of RET introduction. That is, the policy portfolio consists of both FET-based regulations G_{FET} that lower the payoffs from using incumbent FET and RET-based regulations G_{RET} that raise the payoffs from adopting emerging RET, and the simultaneous imposition of the policy portfolio aims for an equalization of intertemporal payoffs from adopting FET and RET and hence provides an incentive of RET adoption when RET becomes available for household use.

$$\begin{aligned} & V_{FET}(T^{I}_{RET}) - \int_{T^{I}_{RET}}^{\infty} G_{FET} \cdot \exp(-r(t - T^{I}_{RET})) \cdot dt \\ & = V_{RET}(T^{I}_{RET}) + \int_{T^{I}_{RET}}^{\infty} G_{RET} \cdot \exp(-r(t - T^{I}_{RET})) \cdot dt \end{aligned} \tag{20}$$

where the left-hand side of Eq. (20) denotes the intertemporal payoffs received from using FET at time T^{I}_{RET} when FET-based policy regulation G_{FET} is put into place to lower the payoffs from using FET. The right-hand side is the intertemporal payoffs received from using RET at time T^{I}_{RET} when RET-based policy regulation G_{RET} is imposed to raise the payoffs from using RET.

Meanwhile, we consider a relevant case where the above-mentioned policy regulations only alter

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[19] Given that the time duration of technology lifecycle is 100 years, and payoff discounting rate is 5%, then we have $\left[T^{M}_{FET} - T^{I}_{FET} - [1 - \exp(-r \cdot (T^{M}_{RET} - T^{I}_{RET}))] / r \right] = 80.13$

the payoffs received from using each individual energy technology (FET and RET), without imposing any disturbance on household's payoffs from using the energy technology in general. In other words, the role that policy regulations play is to induce the transfer of payoffs from using different energy technologies, i.e., the payoff losses of FET users incurred by regulations should be balanced by the payoff gains of RET users, while having no influence on the sector-wide aggregate payoffs from using energy technology. Using the date of RET introduction as the benchmark point, the aggregate payoffs balance imposed on using energy technologies can be expressed as

$$\begin{aligned}&\int_0^{T_{RET}^I}\int_T^{\infty} G_{FET}\cdot\exp(-r(t-T))\cdot dt\cdot dT\\&=\int_{T_{RET}^I}^{\infty}\exp(-r(T-T_{RET}^I))\cdot\int_T^{\infty} G_{RET}\cdot\exp(-r(t-T))\cdot dt\cdot dT\end{aligned}\tag{21}$$

where the life-hand side of Eq. (21) is the payoff losses of all the pre-existing FET users in energy markets when FET-based policy regulations are imposed at time T_{RET}^I. The inner tier of integration corresponds to the intertemporal payoff losses of an individual household adopting FET at time T in the presence of FET-based regulation G_{FET}. The outer tier corresponds to integrating the inflows of all households adopting incumbent FET before policy regulations are in place $T\in[0,T_{RET}^I]$. The right-hand side is the payoff gains of the inflows of all households adopting RET after RET becomes available for end use. The inner tier of integration corresponds to the intertemporal payoff gains of an individual household adopting RET at time T in the presence of RET-oriented policy regulation G_{RET}. The outer tier corresponds to integrating the inflows of all households adopting emerging RET after RET becomes available $T\in[T_{RET}^I,\infty)$, discounted at the benchmark time point T_{RET}^I. We hence obtain the following proposition to summarize the findings.

Proposition 3 *In the above-described model of RET adoption in the presence of energy network externality, the policy portfolio for RET deployment consists of both FET-based regulations G_{FET} that lower the payoffs from using incumbent FET and RET-based regulations G_{RET} that raise the payoffs from adopting emerging RET, and aims to equalize the payoffs from using FET and RET. Moreover, the policy regulations are balanced schemes which impose no disturbance on sector-wide aggregate payoffs from using generic energy technology, in the sense that FET users' payoff losses incurred by G_{FET} should be balanced by RET users' payoffs gains created by G_{RET}. In this case, the levels of policy regulations specific to both incumbent FET and emerging RET can be characterized by the system of equations*

$$\begin{cases}G_{FET}+G_{RET}=p_{RET}-p_{FET}+\beta\cdot n\cdot\left[T_{FET}^M-T_{FET}^I-\dfrac{1-\exp(-r\cdot(T_{RET}^M-T_{RET}^I))}{r}\right]\\[2ex]\dfrac{G_{RET}}{G_{FET}}=r\cdot T_{RET}^I\end{cases}\tag{22}$$

Proof. Substituting the payoff functions $V_{FET}(T_{RET}^{I})$ and $V_{RET}(T_{RET}^{I})$ into Eq. (20) can establish the first equation in this proposition. For the second equation in this proposition, the left-hand side of Eq. (21) charactering the payoff losses of FET users takes an explicit form as

$$\int_{0}^{T_{RET}^{I}}\int_{T}^{\infty} G_{FET}\cdot\exp(-r(t-T))\cdot dt\cdot dT=\frac{G_{FET}}{r}\cdot T_{RET}^{I} \quad ,$$

and the right-hand side of Eq. (21) charactering the payoff gains of RET users is given by

$$\int_{T_{RET}^{I}}^{\infty}\exp(-r(T-T_{RET}^{I}))\cdot\int_{T}^{\infty} G_{RET}\cdot\exp(-r(t-T))\cdot dt\cdot dT=\frac{G_{RET}}{r^{2}} \quad .$$

A balance between payoff losses of FET users and payoff gains of RET users implies the relative level of policy regulations between the two specific energy technologies,

$$\frac{G_{FET}}{r}\cdot T_{RET}^{I}=\frac{G_{RET}}{r^{2}}\Rightarrow\frac{G_{RET}}{G_{FET}}=r\cdot T_{RET}^{I} \quad . \qquad \blacksquare$$

Intuitively, the first equation of this proposition is a straightforward variant of Eq. (15) when there is a simultaneous imposition of both FET-based and RET-based regulations to correct for RET's payoffs gap versus FET. For the intuitions implied by the second equation, as the newly emerging RET is brought into markets at a later date, the incumbent FET can take a longer time to install its network base and hence establish a larger level of installed base network externality. Although this constitutes a stronger inertia that inhibits private adoption of RET, it creates an potential opportunity for regulations in the sense that there is a larger installed base of FET network available for regulators to transfer payoffs to newly emerging RET, thus helping raise the payoffs from adopting RET and foster RET deployment.

5. Conclusions

In designing appropriate policy schemes for RET deployment, traditional well-established wisdom generally centres on bridging the cost gap of high-cost RET versus low-cost FET, given that RET is currently not cost-efficient enough to compete with FET due to the market failure to internalize social and environmental costs associated with environment-polluting FET. While the traditional policy schemes can appropriately correct for environmental externality associated with both types of energy technologies, a characteristic looseness is that it neglects the potential role of network externality that invariably occurs in energy markets.

To capture the unexplored importance of energy network externality for RET deployment, this paper develops an economic model of energy technology adoption that features network externality, where the payoffs derived by a household from adopting a particular type of energy technology are positively related to the size of energy generation, distribution, and service network specific to that technology, which in turn are positively related to the total number of households already adopting that energy technology within the same network. Based on this analytical model, the key findings are that as the incumbent FET – the first commercially available energy technology - has accumulated pervasive deployment and installed base advantage within the energy production, distribution and service network, such a network externality mechanism makes it difficult to dislodge the dominant FET-based technological regime. As a result, the newly emerging RET, once available for commercial use, would face considerable obstacles for large-scale deployment, even if policy regulations have been put in place to eliminate RET's cost disadvantage.

We hence propose that there is a need for a reformulation of RET deployment policy that shifts from traditional wisdoms centring on eliminating cost gap to a new paradigm that corrects for both cost and network externality gaps. In particular, three overarching policy implications are worth noting. First, policy regulations should not be designed merely based on the elimination of RET's cost gap versus FET, because the scope is too narrow to correct for installed base network externality in favour of incumbent FET, thus failing to overcome the internal inertia against RET adoption. Second, specific policy programs should be established to ensure that RET undergoes an equivalent network expansion as the incumbent FET has experienced, so that RET's potential network growth externality can be fully transformed into installed network base externality in favour of RET adoption. It is only when RET and FET accumulate an equivalent size of installed base networks that the payoffs gap attributable to network externality can be eliminated and the level playing field can be created for a rapid and sustained RET deployment. Third, although a large installed base network accumulated by incumbent FET constitutes a strong inertia that inhibits private adoption of RET, it creates an potential opportunity of regulations in the sense that there is a larger installed base of FET network available for regulators to transfer payoffs to newly emerging RET, thus helping raise the payoffs from adopting RET and foster RET deployment.

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Appendix

We rewrite the intertemporal payoffs received from using FET at each point in time $T \in [T^I_{FET}, T^M_{FET}]$ as a sum of integration over two time intervals $[T, T^M_{FET}]$ and $[T^M_{FET}, \infty)$.

$$\begin{aligned} V_{FET}(T) &= \int_T^{\infty} [a+\beta\cdot n\cdot(t-T^I_{FET})-p_{FET}]\cdot\exp(-r(t-T))\cdot dt \\ &= \int_T^{T^M_{FET}} [a+\beta\cdot n\cdot(t-T^I_{FET})-p_{FET}]\cdot\exp(-r(t-T))\cdot dt \\ &\quad +[a+\beta\cdot n\cdot(T^M_{FET}-T^I_{FET})-p_{FET}]\cdot\int_{T^M_{FET}}^{\infty}\exp(-r(t-T))\cdot dt \end{aligned}$$

with the first term in the second line over the time interval $[T, T^M_{FET}]$ is equal to

$$\begin{aligned} &(a-\beta\cdot n\cdot T^I_{FET}-p_{FET})\cdot\int_T^{T^M_{FET}}\exp(-r(t-T))\cdot dt+\beta\cdot n\cdot\int_T^{T^M_{FET}} t\cdot\exp(-r(t-T))\cdot dt \\ &=\frac{a-\beta\cdot n\cdot T^I_{FET}-p_{FET}}{r}\cdot[1-\exp(-r(T^M_{FET}-T))]+\frac{\beta\cdot n}{r}\cdot[T+r^{-1}-(T^M_{FET}+r^{-1})\cdot\exp(-r(T^M_{FET}-T))] \end{aligned}$$

and the second term in the second line over the time interval $[T^M_{FET}, \infty)$ is equal to

$$\frac{a+\beta\cdot n\cdot(T^M_{FET}-T^I_{FET})-p_{FET}}{r}\cdot\exp(-r(T^M_{FET}-T)) \quad .$$

Combining the integration over two time interval, we obtain the intertemporal payoff

$$V_{FET}(T)=\frac{a+\beta\cdot n\cdot(T-T^I_{FET})-p_{FET}}{r}+\frac{\beta\cdot n}{r^2}\cdot[1-\exp(-r(T^M_{FET}-T))] \quad . \qquad \blacksquare$$

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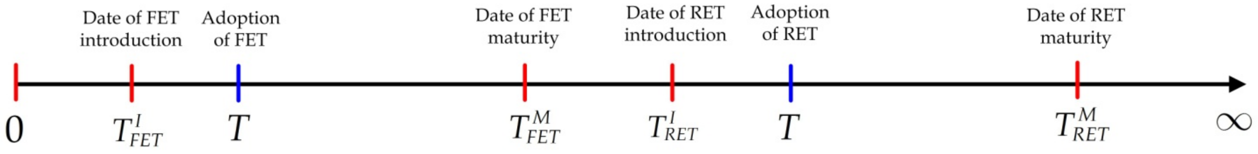

Fig. 1. The timing of technological evolution in energy markets. Over the time frame $T \in [0,\infty)$, the first-mover incumbent fossil energy technology (FET) becomes available to use from the date of technology introduction T^I_{FET}, and the size of FET network grows until the date of technology maturity T^M_{FET}. A household who joins energy markets and adopts FET at any point in time $T \in [T^I_{FET}, T^M_{FET}]$ would benefit from FET's network growth from market entry date T up to FET maturity date T^M_{FET}. After that $[T^M_{FET}, \infty)$, the size of FET network reaches a saturation level. The newly emerging renewable energy technology (RET) becomes available from the date of technology introduction T^I_{RET}, and the size of RET network grows until the date of technology maturity T^M_{RET}. A household who joins energy markets and adopts RET at any time $T \in [T^I_{RET}, T^M_{RET}]$, would benefit from RET's network growth from market entry date T up to RET maturity date T^M_{RET}. After that $[T^M_{RET}, \infty]$, the size of RET network reaches a saturation level. FET and RET are supposed to have the same period of lifecycle from technology introduction to maturity $T^M_{FET} - T^I_{FET} = T^M_{RET} - T^I_{RET}$.

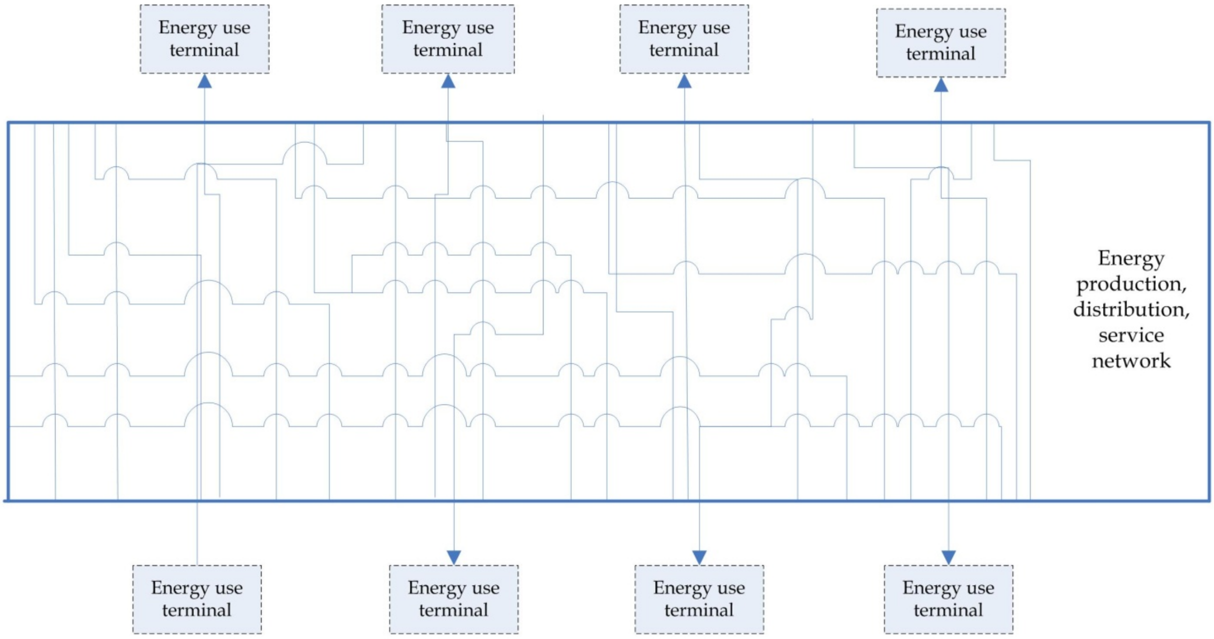

Fig. 2. An illustration of energy technology network. A household directly derives the basic network-independent utility (i.e., thermal energy used for cooking, heating, lighting etc) from energy use terminal. In addition to valuing the basic function from energy use terminal, the household tends to attach network-generated willingness-to-pay to an energy technology with a larger production, distribution, and service network which generally provides end users with more indirect benefits, e.g., economies of scale in production, robustness to operate, efficiency in delivery, convenient access, and repair, maintenance, facility update, and other post-purchase service.

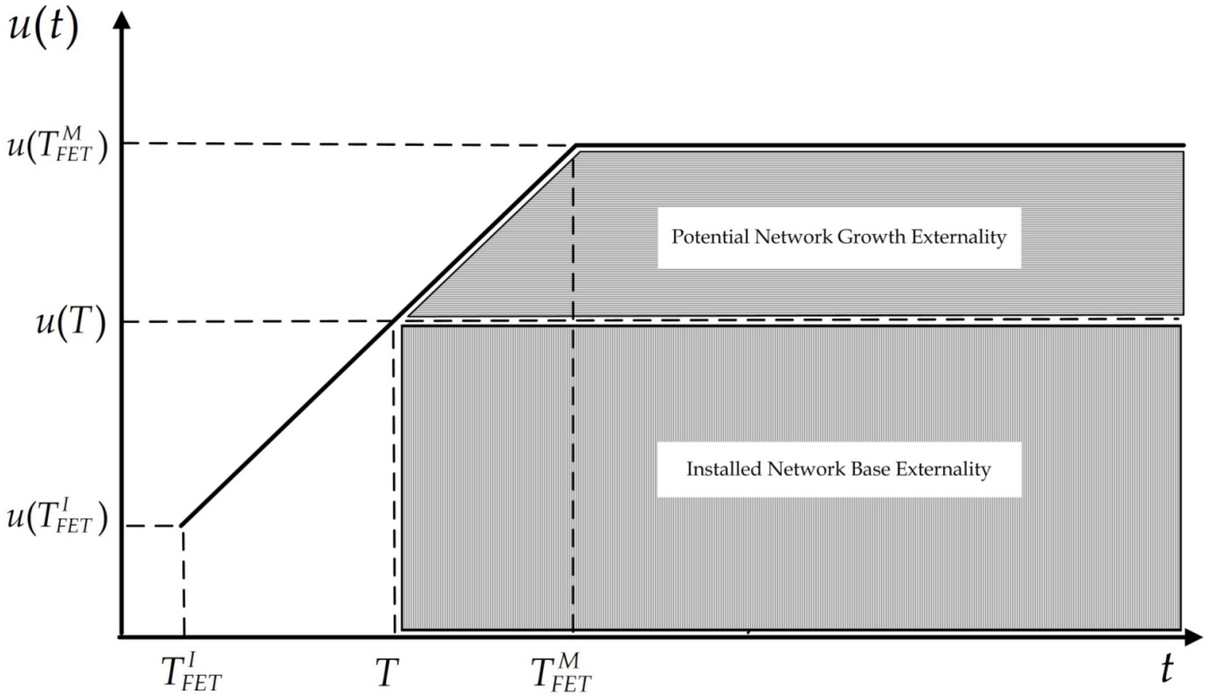

Fig. 3. An illustration of the payoffs received from using fossil energy technology (FET) in the presence of network externality. The intertemporal payoffs received by a household adopting FET at any point in time $T \in [T_{FET}^{I}, T_{FET}^{M}]$ consist of a sum of two parts. 1) Payoffs attributable to *installed network base externality*: at the household entry date $T \in [T_{FET}^{I}, T_{FET}^{M}]$, FET has established an installed network base with a network size of $N(T) = n \cdot (T - T_{FET}^{I})$; 2) Payoffs attributable to *potential network growth effect*: at the household entry date $T \in [T_{FET}^{I}, T_{FET}^{M}]$, FET still has a technology growth potential with network size expanding from T up to FET maturity date T_{FET}^{M}.

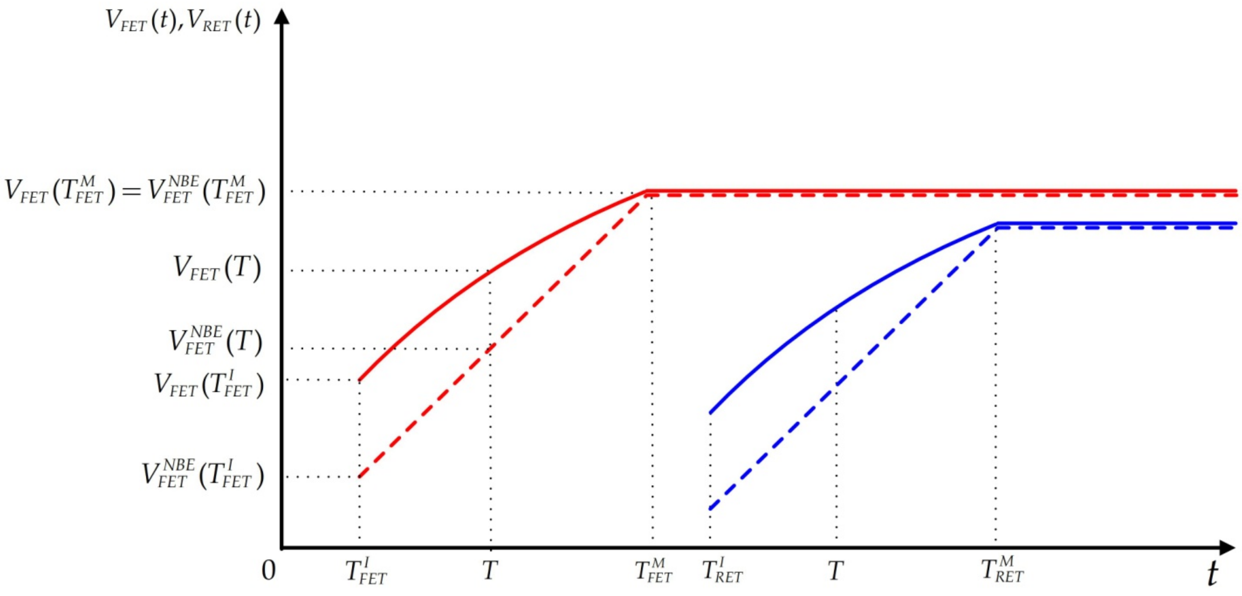

Fig. 4. A graphic illustration of the temporal profiles of payoffs from adopting FET and RET over the time frame $T \in [0, \infty)$. The red solid line corresponds to the payoffs from using FET $V_{FET}(T)$, as a sum of payoffs attributable to installed network base effect $V_{FET}^{NBE}(T)$ (red dash line) and payoffs attributable to potential network growth effect $V_{FET}^{NGE}(T)$ (the gap between red solid and dash lines). The blue solid line denotes the payoffs from using RET $V_{RET}(T)$ as a sum of payoffs attributable to installed network base effect $V_{RET}^{NBE}(T)$ (blue dash line) and payoffs attributable to potential network growth effect $V_{RET}^{NGE}(T)$ (the gap between blue solid and dash lines).