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Welfare Effects of Subsidizing a Dead-End Network of Less Polluting Vehicles

By Antje-Mareike Dietrich and Gernot Sieg*

Overcoming a technological lock-in by means of governmental intervention may be welfare enhancing, even if the implemented technology will be replaced by a better one at a certain time in the future. This holds, if the environmental externality of the implemented technology is small relative to that of the established technology and/or if the network effect of the installed base of service stations is small. If consumers' and politicians' discounting of future payoffs is high, the implementation even of dead-end technologies could be sensible, but policy makers with higher preferences for future payoffs may decide not to overcome lock-in by a new green, but dead-end technology. Governments promoting alternatives to gasoline-driven vehicles must be aware of opposing welfare effects for open-ended and dead-end technologies.
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Keywords: environmental externalities, network effects, private transport, technological change

I. Introduction

Many governments, including those of Germany and France, have committed to reducing anthropogenic greenhouse gases. Because the transport sector is one of the largest producers of greenhouse gases, governments attempt to reduce vehicle emissions. To meet the European Union's goal regarding climate change, namely a 20 percent reduction in greenhouse gas emissions by 2020 (compared to 1990), they advocate green technologies. However, whereas the French government introduced buyers' premiums to promote certain green drivetrain technologies, such as electric vehicles, the German government is focusing on different research initiatives, emphasizing the possibility of future technological improvements. This article identifies possible causes of such different policy actions.

The automobile industry is developing several alternatives to the established gasoline-driven internal combustion engine, such as fuel cells, battery-driven electro motors and biofuel-driven engines. So far, none of these alternative power trains has entered the mass market. Because the usability of a vehicle depends on the network of available service stations, there is a large lock-in effect favoring the established technology. Even if there were decreasing marginal production costs due to economies of scale, there would be a lack of infrastructure, leading to

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a technological lock-in situation. In many European countries, there are taxes on gasoline that, arguably, address greenhouse emission in Pigouvian style. Because a Pigou tax that internalizes external environmental effects does not account for the lock-in advantage of traditional technology, additional governmental intervention is often necessary to induce the adoption of new technologies (Sartzetakis and Tsigaris, 2005). However, any new green technology, such as the battery-driven electro motor, can be replaced entirely by another and better innovation at a later time. Likewise, at the end of the nineteenth century, steam- and battery-driven vehicles dominated the nascent automobile market before the internal combustion engine superseded them. Therefore, even if the technical or environmental advantages of the current battery-driven technology are substantial, it may still constitute a dead-end technology, due to the future development of a better one. Consequently, the question arises as to whether it is reasonable to implement a technology that is dead-end. Would it not be sensible to simply wait for a better technology that may even be compatible with the established network of service stations?

To answer this question, we analyze the interaction of service station networks, greenhouse gas emissions, and uncertain technological progress. We consider a scenario that sooner or later, a technology that is environmentally more sound and, furthermore, compatible with the established network will enter for the market. This could entail a technological leap in the internal combustion engine or a new generation of biofuels, for example, but any other innovation that is compatible with the traditional service station network is possible. Therefore we refer to the currently available clean technology as transitory or dead-end.

From Sartzetakis and Tsigaris (2005), we know that for an open-ended technology, governmental intervention is socially desirable, if the environmental externality of the green technology is small relative to that of the established technology and/or if the network effect of the installed base of service stations is small. In this paper, we analyze not an open-ended, but a dead-end technology and show that even the implementation of a dead-end technology may be socially desirable. In other words, the argument that the available new technology may be only a transitory improvement, should not per se prevent its implementation. Furthermore, compared to the open-end case where only the reduction of emissions and the network effects count, for dead-end technologies, the social valuation of future payoffs also matter. If consumers and politicians discounting of future payoffs is high, the implementation even of dead-end technologies is sensible. Then, it is better not to wait, but to act now.

Our methodical analysis relates to the literature on the economics of networks (Economides, 1996; Birke, 2009). In particular, our model is based on Farrell and Saloner (1986) and in particular follows Sartzetakis and Tsigaris (2005). The former demonstrate that, due to an installed base, network effects can lead to excess inertia so that a superior technology is not adopted. Sartzetakis and Tsigaris (2005) amend the aspect of environmental externalities and apply the model to the automobile sector. They analyze the conditions for a first-best Pigou solution for a framework in which a new technology reaches its matured network size. We supplement this literature by considering dead-end technologies. We compare a scenario with a new green and open-ended technology, which means that no further technology appears subsequently, to a scenario with a dead-end one, which is replaced by a better one. We find that only in the scenario with a dead-end technology, do preferences for future payoffs affect the implementation decision.

Furthermore, our analysis relates to the wide range of literature on the technological transition to alternative-fuel vehicles (Nishihara, 2010; Köhler et al., 2010; Schneider, Schade and Grupp, 2004; Schwoon, 2007; Struben and Sterman, 2008). Whereas some authors, such as Bento (2010) only consider the importance of network effects for the adoption of a new technology, others also consider environmental externalities. For example, Conrad (2009) analyzes the optimal path of investment chosen by a service station owner, and Greaker and Heggedal (2010) model the adoption decision of consumers and loading station owners. Unlike these studies, we argue that even if there were economies of scale on the production side, there would still be a large lock-in effect on the consumer side. Here, we focus on indirect network effects and stress the risk of failing to use a welfare-enhancing technology. We clearly address the trade-off between network effects and environmental externalities for the government's decision to support a new green drivetrain technology. Our results also add the Stern (2006)–Nordhaus (2007) argument that the discounting of future payoffs is essential for efficiently tackling climate change to the discussion on the technological transition to alternative-fuel vehicles.

II. One open-ended Clean Technology

First, we develop a simple scenario with an old "dirty" technology and a new "clean" (green) open-ended technology. As in Sartzetakis and Tsigaris (2005), for simplicity, we assume that one infinitely living automobile user per time unit continuously arrives on the market. All users have a perfectly inelastic demand for a single vehicle and no vehicle buyer demands a different one in the future. Buying generates net-benefit a from the technology's general characteristic of providing mobility. Furthermore, in order to use the technology, frequent use of service stations is necessary, and users prefer a dense network of service stations.[1] As the number of users of a given technology increases, so does the number of service stations catering for this particular technology. We assume that a constant number of new service stations open up with every new user of the corresponding technology and assume that automobile users gain a benefit b from every other user of the network. For simplicity, these basic benefits a and b for consumers will be the same and constant over time for all types of technology (Dirty, Clean, Better) that we discuss in this paper.[2]

Drive-train technologies differ only in terms of how much greenhouse gases they emit. Each user of the current dirty technology D, here, gasoline-driven vehicles, emit the environmental externality ϵ_D. We therefore implicitly assume that the demand for driving is constant.[3]

Technology D enters the market at $T^d = 0$. The net present value of the benefit (NPV) to a new user arriving at time T, if D is used until infinity, is

$$D(T) = \int_T^{\infty} (a + b \cdot t) e^{-r(t-T)}\, dt = \frac{a + b \cdot T}{r} + \frac{b}{r^2}, \tag{1}$$

[1] For electric vehicles, it is currently unclear, whether charging at home by vehicle owners can substitute for a network of loading stations. In any event, for trips beyond the loading range of the vehicle, some kind of loading station is of course required.

[2] However, see Proost and Van Dender (2012) for an overview of disadvantages for consumers and the costs of available drive-train technologies.

[3] See Small (2012) on determinants of the demand for driving including the rebound effect of cost reductions.

with r being the time discount rate. For $r = 0$, future payoffs are valued equally to present payoffs, whereas for increasing r, future payoffs are valued less.

At time $T^c > 1/r$, a new technology, such as electric vehicles, is ready for the market. Because it emits $\epsilon_C < \epsilon_D$ less than technology D, we call it clean technology C. We assume that both the new technology and the old technology are equally well designed to serve the basic mobility needs of users. However, due to $D's$ dense network of service stations, which is proportional to the already installed base T^c, rational new users, who do not consider the external effects, choose the old technology D, a process known as excess inertia (Farrell and Saloner, 1986).[4]

The government may induce a switch towards the clean technology from T^c, by paying a subsidy $\hat{s}$ for C-users, such that the benefit of buying C is not smaller than the benefit of buying D. Let us assume that the government can commit to such a policy and that the subsidy is successful in influencing all new users at $T \geq T^c$ to choose C. We assume that new users choose the cleaner technology out of ϵ-altruism; that is, because both technologies offer the same private utility, users choose the technology that is better for society. For each user entering the market at $T > T^c$, there is already a network of size $T - T^c$. The NPV for a user at time $T \geq T^c$ if C is used to infinity by all the following users equals

$$C(T) = \int_T^\infty [a + b(t - T^c)]e^{-r(t-T)}\, dt = \frac{a + b\,(T - T^c)}{r} + \frac{b}{r^2}. \tag{2}$$

If all users from T^c use technology C, then the network of D stops growing. Therefore, the NPV of a user choosing D at $T > T^c$, if the last user of D was at time T^c, is

$$\tilde{D}(T) = \int_T^\infty [a + b \cdot T^c]e^{-r(t-T)}\, dt = \frac{a + b \cdot T^c}{r}. \tag{3}$$

Figure 1 shows the network's growth for both technologies over time. The solid line describes the path of the D-network. It grows from $T^d = 0$ until T^c, at which point it stgnates. The dashed line represents the D-path if the second technology does not appear. The thin line shows the path of the C-network. Starting at T^c, it has the same size as technology D at $2T^c$. Accordingly, it is larger than the D-network.

LEMMA 1: *If the government pays the subsidy*

$$\hat{s}(T) = \begin{cases} \frac{b(2T^c - T)}{r} - \frac{b}{r^2}, & \textit{for } T^c \leq T \leq 2T^c - \frac{1}{r} \\ 0, & \textit{for } T > 2T^c - \frac{1}{r} \end{cases}, \tag{4}$$

then all users entering at $T \geq T^c$ choose technology C.

Proof: See Appendix.

As long as $\tilde{D}(T) > C(T)$, the government must pay the subsidy $\hat{s}(T)$, which is shown in Figure 2. This compensates the early C-users, because they cannot use

[4] If $T^c < 1/r$, then buying C is optimal, if users assume that all new users will buy C as well. Therefore, no subsidy is needed. Therefore, $T^c = 1/r$ is the critical installed base. If the network exceeds this size, there is a lock-in that cannot be overcome without governmental intervention (Arthur, 1989; David, 1985).

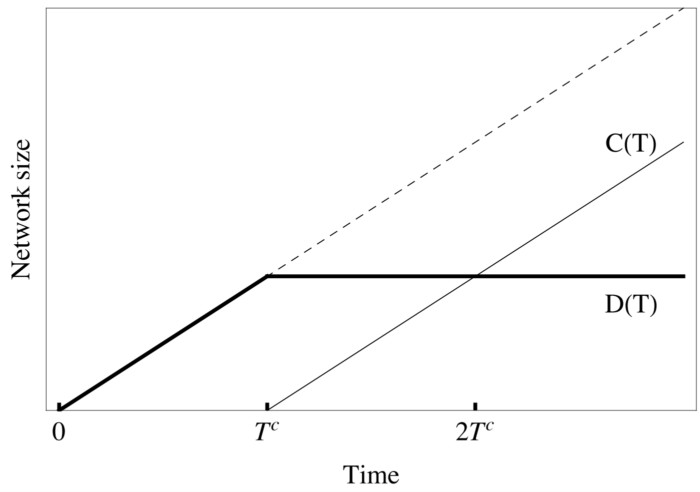

FIGURE 1. THE ONE GREEN TECHNOLOGY SCENARIO

the installed larger network of technology D. Because the disadvantage associated with the technology C declines with a growing network of C-service stations, the subsidy for the early C-users can be reduced each period until it terminates at $2T^c - \frac{1}{r}$. At this point, new users opt for the C-technology, even if there is no governmental intervention. Although the D-network of service stations is still larger the C-network at this point, rational users expect the C-network to grow whereas the D-network has already reached its final size. Therefore, consumers no longer lock-in technology D.

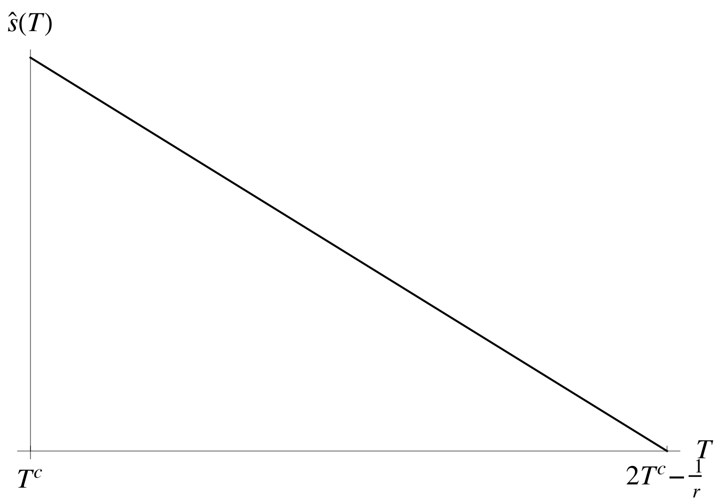

FIGURE 2. SUBSIDY IN THE ONE GREEN TECHNOLOGY SCENARIO

PROPOSITION 1: *Implementing technology C is welfare enhancing if $\epsilon_D - \epsilon_C > 2bT^c$.*

Proof: See Appendix.

Proposition 1 shows that the government can enhance social welfare by overcoming lock-in and thus by subsidizing the new green technology C. The condition states the opposing effects of environmental benefits and the network effect. The use of the lower-emission technology C reduces environmental externalities and thus enhances welfare. Furthermore, because the utility of an automobile user depends on the density of a service infrastructure, using technology C reduces welfare because it is not compatible with the installed D-network. Therefore, subsidizing technology C is only welfare enhancing if the environmental benefit of using the lower-emission technology C exceeds the benefit derived by all users being in the same network of service stations.

III. Dead-end Clean and Better Technology

We now further examine technological improvement. Even an existing technology, such as the internal combustion engine, improves continually over time. Even if technology C, such as a battery-driven electric motor, is cleaner than the internal combustion engine at time T^c, this may change in the future. If the technological progress of C is slower than that of D, it is possible that at some time in the future, the internal combustion engine will be better from an environmental point of view, compared to the battery-driven electric motor. We refer to this as "better" technology B, because its external effect $\epsilon_B < \epsilon_C$ is smaller than that of C and it is compatible[5] with the old D-network.

To reassess the argument that, because of future developments, it makes no sense to subsidize a (potentially) dead-end technology, we consider a scenario that does not favor technology C. We assume that sooner or later, the better technology B will inevitably be ready for the market. However, to address the uncertainty of future developments, it is not clear exactly when this technology will be ready for the market. By introducing technology B, the clean technology C becomes a dead-end one, because it is associated with higher environmental externalities and its network stops growing as soon as technology B enters the market, as all users at $T \geq T^b$ choose technology B due to ϵ-altruism.[6]

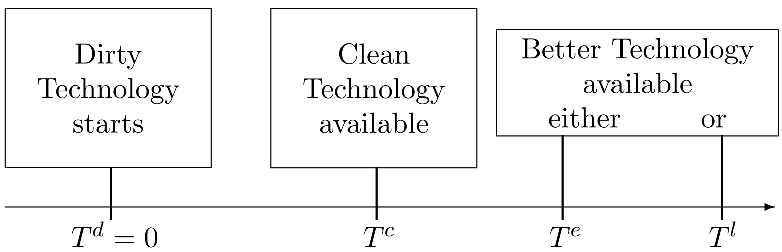

FIGURE 3. TIMING OF EVENTS

As shown in Figure 3, the timing of events is as follows. As in Section 2, the model begins at $T^d = 0$ with technology D. At T^c, the clean technology C enters

[5]If technology B is assumed to be incompatible with the network of technology D, further governmental intervention is needed to overcome the technological lock-in.

[6]As an anonymous referee remarked, if the automobiles are not infinitely durable, the old network of D service stations may be quite small or completely disappear completely by the time technology B is introduced. This condition would lead to lower subsidies for technology C and an earlier lock-in into technology C than in our analysis.

the market. The better technology arrives either with probability p early at time $T^b = T^e$ or, with probability $1 - p$, late at time $T^b = T^l$.

Because we assume $T^c > 1/r$, the D-network has reached its critical installed base, causing a lock-in situation. Consequently, new users do not choose technology C without governmental intervention. In our scenario, all users choose technology C from T^c to T^b, because there are subsidies that are paid by the government. Because of $T^d = 0$, the networks of technology D and the subsidized technology C are the same size at $2T^c$. We focus on the case that the environmentally dead-end technology is subsidized in order to overcome the economic lock-in situation, that is, $T^e < T^l < 2T^c + 1/r$. Because $T^l < 2T^c + 1/r$, we avoid another lock-in situation with technology C, so that technology B never needs to be subsidized. Rational new users choose technology B, if they expect future users to do the same.

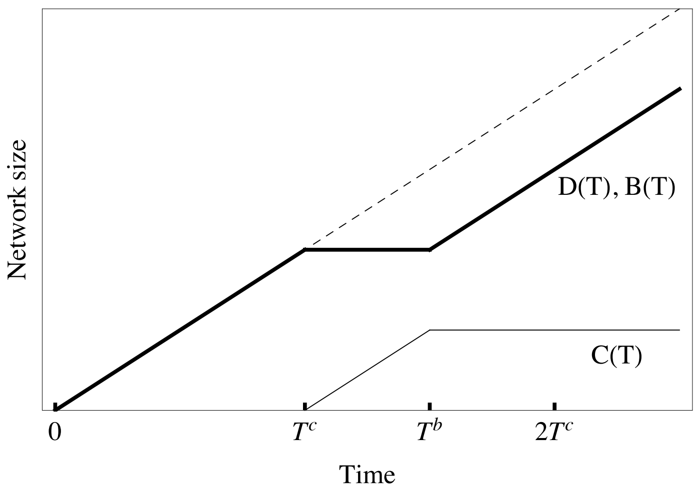

FIGURE 4. SCENARIO WIN WHICH $T^b < 2T^c$

Figure 4 shows the network's growth for the three technologies for the scenario with technology B entering at $T^b < 2T^c$. The solid line describes the path of the D-network. Here, it increases from $T^d = 0$ until T^c. It then stops growing for the period T^c, when C is chosen, which continues until T^b, when B enters the market. The D-network then continues to expand, because of the compatibility of technology B with the D-network. In this scenario, the C-network never reaches the size of the D/B-network. As the thin line shows, it only grows from T^c until T^b. After that, it remains at the size reached at T^b. Figure 5 shows the evolution of the networks within in the scenario with $T^b > 2T^c$. In this scenario, the C-network may exceed the size of the D-network at $2T^c$. It stops growing when B enters the market, and because the D/B-network continues to expand, the latter again exceeds the former.

Considering that B definitely arrives in a future period, the NPV for the users of D changes as well. The D-network does not end at T^c, but continues to grow at T^b when B appears. To calculate the NPV, we must also consider that this can occur at two different points in time. Therefore, the NPV for one user of the

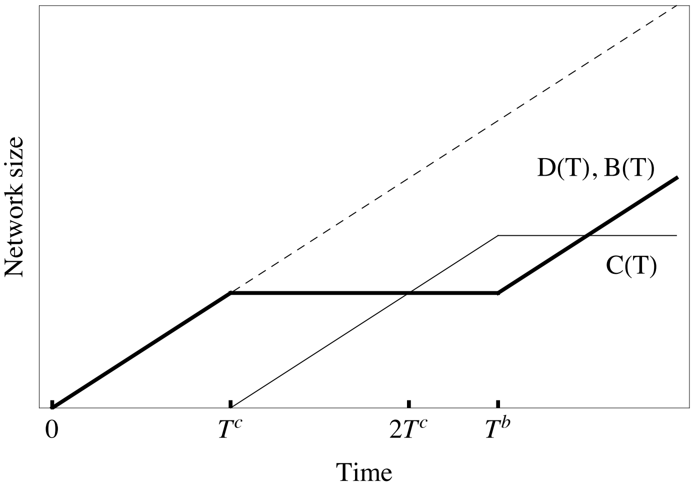

FIGURE 5. SCENARIO IN WHICH $T^b > 2T^c$

D-technology who enters the market at $T < T^c$ adds up to

$$\begin{aligned} D_2(T) = &\int_T^{T^c} [a + b \cdot t] e^{-r(t-T)}\, dt + p \left(\int_{T^c}^{T^e} [a + b \cdot T^c] e^{-r(t-T)}\, dt \right. \\ &\left. + \int_{T^e}^{\infty} [a + b(t - (T^e - T^c))] e^{-r(t-T)}\, dt \right) \\ &+ (1-p) \left(\int_{T^c}^{T^l} [a + b \cdot T^c] e^{-r(t-T)}\, dt \right. \\ &\left. + \int_{T^l}^{\infty} [a + b(t - (T^l - T^c))] e^{-r(t-T)}\, dt \right) \\ = &\frac{a + b \cdot T}{r} + \frac{b(1 - e^{-r(T^c - T)} + p \cdot e^{-r(T^e - T)} + (1-p) \cdot e^{-r(T^l - T)})}{r^2}. \end{aligned} \tag{5}$$

From T^c onward in our scenario, all users choose technology C. Due to the arrival of technology B, their benefit also changes. Now, they end up in a dead network. When exactly this occurs depends on the probability p. The NPV for one of these users appearing at $T^c < T < T^e$ equals

$$\begin{aligned} C_2^e(T) = &p \left(\int_T^{T^e} [a + b(t - T^c)] \cdot e^{-r(t-T)}\, dt \right. \\ &\left. + \int_{T^e}^{\infty} [a + b(T^e - T^c)] \cdot e^{-r(t-T)}\, dt \right) \\ &+ (1-p) \left(\int_T^{T^l} [a + b(t - T^c)] \cdot e^{-r(t-T)}\, dt \right. \\ &\left. + \int_{T^l}^{\infty} [a + b(T^l - T^c)] \cdot e^{-r(t-T)}\, dt \right) \\ = &\frac{a + b(T - T^c)}{r} + \frac{b(1 - p \cdot e^{-r(T^e - T)} - (1-p) \cdot e^{-r(T^l - T)})}{r^2}. \end{aligned} \tag{6}$$

Because, after time T^e, technology B definitely arrives at time T^l, the NPV for users entering the market at $T^e < T < T^l$, must be calculated as

$$\begin{aligned} C_2^l(T) =& \int_T^{T^l} [a + b(t - T^c)] \cdot e^{-r(t-T)}\, dt \\ &+ \int_{T^l}^{\infty} [a + b(T^l - T^c)] \cdot e^{-r(t-T)} \\ =& \frac{a + b(T^c - T)}{r} + \frac{b(1 - e^{-r(T^l - T)})}{r^2}. \end{aligned} \tag{7}$$

The NPV of the users choosing D at $T^c < T < T^e$, if the last user of D was at time T^c, equals

$$\tilde{D}_2^e(T) = \frac{a + b \cdot T^c}{r} + \frac{b(p \cdot e^{-r(T^e - T)} + (1-p) \cdot e^{-r(T^l - T)})}{r^2}, \tag{8}$$

and for those users choosing D at $T^e < T < T^l$, it equals

$$\tilde{D}_2^l(T) = \frac{a + b \cdot T^c}{r} + \frac{b \cdot e^{-r(T^l - T)}}{r^2}. \tag{9}$$

When technology B appears, the government stops paying subsidies to the users of C. Therefore, the government must compensate these users not only for not using the D-network, but also for ending up in the dead network. Failing such compensation, they would choose D.

LEMMA 2: *If the government pays*

$$\hat{s}_C(T) = \begin{cases} \frac{b(2T^c - T)}{r} - \frac{b\left(1 - 2p \cdot e^{-r(T^e - T)} - 2(1-p) \cdot e^{-r(T^l - T)}\right)}{r^2}, & \text{for } T^c \leq T < T^e \\ \frac{b(2T^c - T)}{r} - \frac{b(1 - 2e^{-r(T^l - T)})}{r^2}, & \text{for } T^e \leq T \leq T^l \end{cases}, \tag{10}$$

from T^c till T^b, then all users entering at $T^c \leq T < T^b$ choose technology C.

Proof: See Appendix.

As long as $\tilde{D}_2(T) > C_2(T)$, the government must pay the subsidy $\hat{s}_C(T)$, as shown in Figure 6. There are three effects determining the amount of the subsidy. Firstl¡, because the C-network grows while the D-network stagnates, the subsidy can be reduced each period. Secondly, at time T^e, there is a jump discontinuity. This is because if technology C does not arrive at T^e, it will not arrive before T^l, causing the C-network to grow by $T^l - T^c$. Less compensation is necessary, because the C-network is larger. Thirdly, after a certain T_{min}, the amount of the subsidy increases again. The later users of technology C need more compensation for choosing it, because they know that the growth of their network will soon end.

Welfare analysis

Welfare W is defined as the sum of consumer rent, which is the sum of the utility derived from using technology C or D or B (which are free of charge),

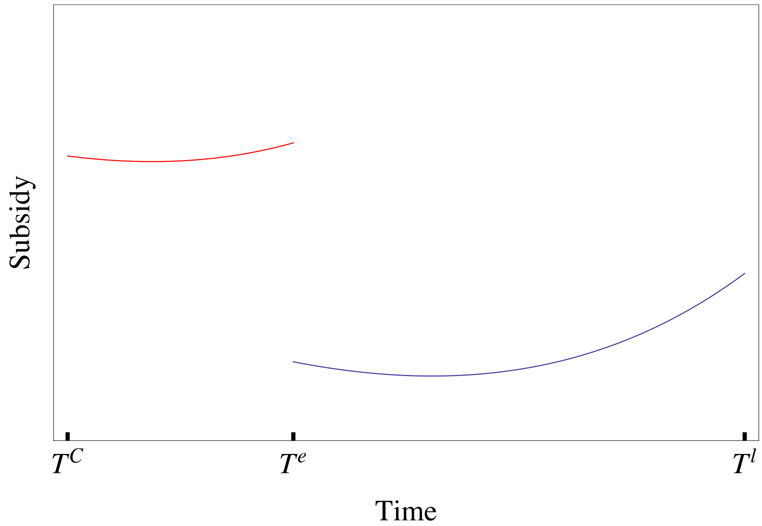

FIGURE 6. Subsidy in the two-green-technology scenario

minus the external effect from using the technologies. By doing so, we assume that the source of governmental payments is a non-distortionary tax. In reality, however, most taxes are distortionary and therefore, an additional cost has to be considered. Hirte and Tscharaktschiew (2012) show, for example, that these additional costs may be decisive as to whether or not it is welfare enhancing to subsidize electric vehicles in metropolitan areas. However, paying subsidies is not the only policy for implementing the new technology. A prohibitive taxation on buying the dirty one or even banning the dirty one outright will have the same welfare effects in our simple model. The distribution of costs and benefits, however, will be different. In the case of a prohibitive tax or a ban of the dirty technology, the new adaptors bear most of the cost, because they are in the smaller network. By receiving a subsidy, new adaptors acquire the same utility as if they had joined the old network. Because the environmental benefits are shared equally, the welfare effects of subsidies, taxes and bans are similar, but the utility is shared more evenly between consumers in case of subsidies.[7] To summarize, with our approach, subsidies $\hat{s}_C$ are funded by a lump-sum tax, paid by the government and received by the consumers and therefore cancel each other out when calculating the overall welfare. Subsidies then change welfare only indirectly by determining the type of technology used.

In analyzing welfare change due to the technological change, we must examine the different paths depending on the technology chosen.

Without governmental intervention, technology C cannot be achieved in the market, because of the network externalities resulting from the service infrastructure of technology D. New users will choose D from T^d onwards until technology B enters the market. They then choose the better technology B out of ϵ-altruism.

[7] However, in reality consumers (and technologies) are heterogenous and therefore subsidies, taxes and bans differ in many other respects not considered here (Proost and Van Dender, 2012) .

At time T^c, expected social welfare without governmental intervention equals

$$\begin{aligned} W(T^c) =& p \cdot \left(\int_0^{T^e} \left[\int_t^{\infty} [a + b \cdot \tau - \epsilon_D] \cdot e^{-r(\tau - t)} \, d\tau \right] e^{-r(t-T^c)} dt + \right. \\ & \left. \int_{T^e}^{\infty} \left[\int_t^{\infty} [a + b \cdot \tau] \cdot e^{-r(\tau - t)} \, d\tau \right] e^{-r(t-T^c)} dt \right) + \\ & (1-p) \cdot \left(\int_0^{T^l} \left[\int_t^{\infty} [a + b \cdot \tau - \epsilon_D] \cdot e^{-r(\tau - t)} \, d\tau \right] e^{-r(t-T^c)} dt + \right. \\ & \left. \int_{T^l}^{\infty} \left[\int_t^{\infty} [a + b \cdot \tau] \cdot e^{-r(\tau - t)} \, d\tau \right] e^{-r(t-T^c)} dt \right), \end{aligned} \tag{11}$$

which is the reference scenario in the following analysis. (For the calculation, see equation A11 in the Appendix.) As just described, in this scenario, all users choose technology D with the external effect ϵ_D from $T^d = 0$ until T^b, and from T^b onwards, they choose technology B with the external effect $\epsilon_B = 0$. The first term calculates the welfare for the case that technology B arrives at the early time T^e, whereas the second term calculates for the case that technology B arrives at the later T^l.

Social welfare with the use of clean technology equals

$$W_{\hat{s}}(T^c) = W_{D_{\hat{s}}} + W_{C_{\hat{s}}} + W_{B_{\hat{s}}}, \tag{12}$$

which is the alternative scenario for the government. In this scenario, there are three types of users, according to the technology they are using. The first group enters the market before T^c, so that they must take technology D and obtain $W_{D_{\hat{s}}}$. The second group are those choosing technology C, as they arrive in the later period from T^c to T^b. Finally, the users entering the market from T^b onwards use technology B. To calculate the welfare $W_{i_{\hat{s}}}$ for each of these groups $i \in \{B, C, D\}$, we must also consider the two possible times for technology B to appear. The welfare for the groups is calculated separately in the Appendix (see equations (A12), (A13) and (A14)).

At time T^c, the government must decide whether or not to implement the clean technology by paying subsidies. Because the government maximizes social welfare, it should subsidize technology C, if $W \leq W_{\hat{s}}$ holds.

PROPOSITION 2: *If and only if*

$$\epsilon_D - \epsilon_C > \frac{2b[T^c + p(T^e - 2T^c)e^{r(T^c - T^e)} + (1-p)(T^l - 2T^c)e^{r(T^c - T^l)})]}{1 - pe^{r(T^c - T^e)} - (1-p)e^{r(T^c - T^l)}} =: \tilde{\epsilon}$$

then $W < W_{\hat{s}}$*, i.e. it is welfare-enhancing to implement the dead-end technology* C*.*

Proof: See Appendix.

Proposition 2 states that even if technology C is dead-end, it may be socially desirable to subsidize its usage to overcome a technological lock-in. As for an open-ended technology, by implementing technology C, on the one hand, social welfare is enhanced, due to the reduction of greenhouse gas emissions. However, on the other hand, implementing technology C reduces social welfare, as it is not compatible with the installed D-network. The consequence of choosing technology C is the existence of two incompatible networks. Therefore, the welfare-enhancing government should intervene and implement the dead-end technology C only if the reduction in the external effect exceeds the benefit of compatibility. Proposition 2 also shows that in the case of a dead-end technology, the time discount rate and the expected lifetime of technology C are relevant to determining the critical $\tilde{\epsilon}$.

As observed in Proposition 2, the size of the critical $\tilde{\epsilon}$ depends on several distinct factors and the influences of these factors in the case that the new green technology is a dead-end one, in comparison to the case of an open-ended technology, are analyzed in the following Corollaries.

COROLLARY 1: *It holds that* $\partial\tilde{\epsilon}/\partial b > 0$.

Proof: See appendix.

Parameter b describes user preference for a dense network and thereby determines the network effect. If the benefit from the installed base is large, then $\Delta\epsilon := \epsilon_D - \epsilon_C$ must also be larger so that $W_{\hat{s}} > W$ holds. Therefore, if the strength of the network effect increases, the emission reduction must increase as well. Otherwise, the use of technology C would not enhance welfare. In other words, the preferences for a compatible infrastructure determine whether the government should support a certain new clean technology that leads to a certain emission reduction. This holds for both cases of technology C being an open- or a dead-end technology.

COROLLARY 2: *It holds that* $\partial\tilde{\epsilon}/\partial r < 0$.

Proof: See appendix.

Discounting future welfare only matters within the decision-making process, if technology C is going to be dead-end. If future payoffs are discounted substantially, that is, if the future is not highly valued, then $\Delta\epsilon$ may be small, and $W_{\hat{s}} > W$ continues to hold. This can be explained as follows: by using the new, less polluting technology, a positive welfare effect arises immediately from the emission reduction. Starting at time T^c, this positive welfare effect arises each period at the constant amount $\epsilon_D - \epsilon_C$. Meanwhile, the network of technology C grows each period by the rate t. Therefore, the number of missing users in the D/B-network increases each period and, therefore, for T^c to T^b, with each new user choosing technology C each period, there are more users suffering from the incompatibility of the two networks. Therefore, the negative welfare effect of the incompatibility grows each period and remains constant after T^b. A large r values this welfare loss less. Therefore, it is socially desirable to support technology C, even for a smaller $\Delta\epsilon$. The time discount rate does not matter for open-ended technologies, because, when the decision of whether to subsidize is made, both the size of the emission reduction and the extent of incompatibility are determined and increase after T^c each period to infinity at the same rate.

COROLLARY 3: *The expected network size E of Technology C is*

$$E = p(T^e - T^c) + (1-p)(T^l - T^c) = pT^e + (1-p)T^l - T^c \quad (13)$$

It holds:

$$\partial E/\partial T^e > 0,\ \partial E/\partial T^l > 0,\ \partial E/\partial T^c < 0 \text{ and } \partial E/\partial p < 0. \quad (14)$$

For the decision on whether to subsidize the dead-end technology C, its expected network size is also important. The expected network C increases with T^e and T^l and decreases with the probability p that technology B will arrive at the early time T^e and T^c. The size of the C-network has three effects on welfare. First, a large C-network reduces the utility for users of technologies D and B, because their network is smaller. Second, a late arrival of technology B means that in the meantime, the dirty technology will produce large emissions if technology C is not subsidized into use. Third, a large expected network size of technology C results in a late arrival of the better technology B and thus increases emissions. However, because technology B is used even in the status quo scenario of no subsidies, this is irrelevant for the decision on whether to subsidize or not. If the first (second) effect exceeds the second (first), a larger expected network size increases (decreases) the positive welfare effect of the subsidy.

One aim of this paper has been to reassess the statement that implementing dead-end or transitory technologies is not sensible. Therefore, we made assumptions that favor the initial technology. For example, the positive network effects increase linearly with the size of the network and are unbounded from above. If marginal network effects are decreasing, the argument in favor of implementing the dead-end technology is even stronger, i.e. the emission reduction a clean technology offers could be smaller. We assumed infinitely living users who are unable to switch technologies. The more realistic assumption that the life span of the vehicle is limited and that consumers are able to switch, do not change the lock-in problem and the need of governmental action to overcome it. Furthermore, because the initial network size is then limited, the argument for implementing the clean technology becomes stronger. However, the network size of the environmentally better technology declines and it is no longer certain that the better (final) technology is implemented without governmental intervention.

Our results can be applied to the case of electric vehicles, as the currently most heavily subsidized alternative to gasoline-driven vehicles. Corollary 1 states that when the network effect is strong, for example, because the installed base is large, intervention is only justified if the environmental benefit is significant. There is, however, currently no appropriate network of loading and service stations for electric vehicles. Therefore, the network effect of the already installed service stations network for gasoline-driven vehicles is large. Accordingly, the greenhouse gas reduction of battery-driven mobility must also be large. Otherwise, government intervention would not enhance welfare. Considering German power generation, which emitted on average 601 g carbon dioxide per kWh in 2012 (Icha, 2013), it would hardly enhance social welfare to implement electric vehicles. A small (midsize) electric vehicle using 16 (22) kWh to drive 100 km then emits 9.6 (13.2) kg carbon dioxide, whereas in 2012, the average emissions of new conventional cars in Germany were 14.1 kg per 100 km (Jato Consult, 2013).

However, if the electricity could be gained from energy sources featuring low greenhouse gas emissions, such as wind or solar, then the use of battery-driven vehicles would significantly reduce greenhouse gas emissions. If we examine French power generation, which emits on average less than 100 g carbon dioxide per kWh, it could be welfare enhancing to promote battery-driven mobility.[8]

It is currently unclear whether or not electric vehicles are a dead-end technology.

[8]This only holds if we focus on greenhouse gas emissions and do not consider other environmental effects.

The subsidization of an open-ended technology, see Proposition 1, could be welfare enhancing, even if the ecological effect was much smaller. This leads to another argument for different policy actions, due to diverse expectations about the life span of the new green technology. If a government expects battery-driven vehicles to be the future open-ended technology, it may promote it by paying subsidies. A government that expects battery-driven vehicles only to be a temporary dead-end technology has less incentive to subsidize.

Finally, as Corollary 2 states, if electric vehicles were a dead-end technology, the decision on whether to subsidize it would also depend on the relative weight of economic welfare of different households or generations over time. This connection is discussed in depth by Stern (2006) and Nordhaus (2007). Politicians' preferences for future payoffs could be another reason why some governments invest in a dead-end technology and others do not. Governments with a high valuation of the future would prefer not to invest in a dead-end technology, even if the emission reduction would be substantial, whereas those with a lower valuation of the future would invest. This is not in line with the stereotype of a green policy maker, who discounts the future less and thus invests more in green technologies. There are consequences for decision-making at time T^c. For a given emission reduction, policy makers with a higher preference for future payoffs may decide not to overcome the lock-in situation by a new green technology, whereas those with a lower preference for future payoffs may decide to subsidize a green technology. From this perspective, a further reason that a new green, but dead-end technology may be subsidized today, could be that policy makers neglect the long-run consequences of their actions.

IV. Conclusion

In the presence of environmental externalities, it may be welfare enhancing to overcome a technological lock-in by means of governmental intervention. As our model shows, this may also hold for a dead-end technology that emerges within a process of technological transition. Within our model, there is an opposing effect between the environmental benefits of using a cleaner technology and the losses caused by incompatible networks. The reduction of environmental externalities enhances welfare, whereas network incompatibility reduces utility for all consumers. The important parameters within the analysis are the difference between the environmental externalities and the strength of the network effect. In addition, the governmental decision of whether to subsidize a dead-end technology also depends on the value of future payoffs, that is, the time discount rate. It is desirable to subsidize the new green technology, if its environmental externality is small relative to that of the established technology and/or if the strength of the network effect is small. Furthermore, we find that in a market with positive externalities due to network effects, where environmental and consumer externalities are discounted by the same time discount rate, policymakers with a higher preference for future payoffs may decide not to overcome the lock-in situation by a new green, but dead-end technology.

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Mathematical Appendix

Proof of Lemma 1

As long as $\tilde{D}(T) > C(T)$, the government must pay a subsidy $\hat{s}$. Because the network of technology C grows with each new user, the subsidy can be reduced over time. Let (as in 4)

$$\hat{s}(T) = \begin{cases} \frac{b(2T^c - T)}{r} - \frac{b}{r^2}, & \text{for } T^c \leq T \leq 2T^c - \frac{1}{r} \\ 0, & \text{for } T \geq 2T^c - \frac{1}{r} \end{cases}. \tag{A1}$$

Then, for $T^c \leq T \leq 2T^c - \frac{1}{r}$,

$$\begin{aligned} C(T) + \hat{s}(T) =& \frac{a + b\,(T - T^c)}{r} + \frac{b}{r^2} + \frac{b\,(2T^c - T)}{r} - \frac{b}{r^2} \\ =& \frac{a + b \cdot T^c}{r} = \tilde{D}(T), \end{aligned} \tag{A2}$$

and all users choose technology C. If $T \geq 2T^c - \frac{1}{r}$, then $\hat{s}(T) = 0$ and $C(T) > \tilde{D}(T)$, and all users choose technology C. □

Proof of Proposition 1

To prove Proposition 1, we have to calculate the status quo welfare W_N for the scenario without implementation of C

$$\begin{aligned} W_N(T^c) =& \int_0^\infty \left(\int_t^\infty (a + b \cdot \tau - \epsilon_D) e^{-r(\tau - t)}\, d\tau \right) e^{-r(t - T^c)}\, dt \\ =& \frac{(2b + (a - \epsilon_D) r) e^{rT^c}}{r^3} \end{aligned} \tag{A3}$$

and W_S, where C is implemented

$$\begin{aligned} W_S(T^c) =& \int_0^{T^c} \left(\int_t^{T^c} [a + b \cdot \tau - \epsilon_D] e^{-r(\tau - t)}\, d\tau \right. \\ &+ \left. \int_{T^c}^\infty [a + b \cdot T^c - \epsilon_D] e^{-r(\tau - t)}\, d\tau \right) e^{-r(t - T^c)} dt \\ &+ \int_{T^c}^\infty (\int_{T^c}^\infty [a + b(\tau - T^c) - \epsilon_C] e^{-r(\tau - t)}\, d\tau) e^{-r(t - T^c)} dt \\ =& \frac{r\left(a e^{rT^c} - \epsilon_D (e^{rT^c} - 1) - \epsilon_C - 2bT^c\right) + 2b e^{rT^c}}{r^3}. \end{aligned} \tag{A4}$$

For $\epsilon_D - \epsilon_C \geq 2bT^c$,

$$\frac{\epsilon_C - \epsilon_D + 2bT^c}{r^2} \leq 0 \iff W_N - W_S \leq 0 \iff W_N \leq W_S \tag{A5}$$

holds. □

Proof of Lemma 2

As long as $\tilde{D}_2(T) > C_2(T)$, the government must pay $\hat{s}_C$. Because the network of C grows with each new user, then $\hat{s}_C$ is also a function of T.

Let (as in 10)

(A6)
$$\hat{s}_C(T) = \begin{cases} \frac{b(2T^c-T)}{r} - \frac{b\left(1-2p\cdot e^{-r(T^e-T)}-2(1-p)\cdot e^{-r(T^l-T)}\right)}{r^2}, & \text{for } T^c \le T < T^e \\ \frac{b(2T^c-T)}{r} - \frac{b(1-2e^{-r(T^l-T)})}{r^2}, & \text{for } T^e \le T \le T^l \end{cases}.$$

Because $T < 2T^c + \frac{2(1-p)e^{-r(T^l-T)}+2pe^{-r(T^e-T)}-1}{r}$,

$$\frac{b(2T^c-T)}{r} - \frac{b\left(1-2p\cdot e^{-r(T^e-T)}-2(1-p)\cdot e^{-r(T^l-T)}\right)}{r^2} > 0 \quad \text{(A7)}$$

$$\iff \tilde{D}_2^e(T) - C_2^e(T) > 0 \iff \tilde{D}_2^e(T) > C_2^e(T), \quad \text{(A8)}$$

and all users at $T^c \le T < T^e$ choose C. If $T > 2T^c + \frac{2(1-p)e^{-r(T^l-T)}+2pe^{-r(T^e-T)}-1}{r}$, $\hat{s}_C(T) = 0$ and $C_2^e(T) > D_2^e(T)$, and all users choose technology C.

Because $T < 2T^c + \frac{2e^{-r(T^l-T)}-1}{r}$,

$$\frac{b(2T^c-T)}{r} - \frac{b(1-2e^{-r(T^l-T)})}{r^2} > 0 \quad \text{(A9)}$$

$$\iff \tilde{D}_2^l(T) - C_2^l(T) > 0 \iff \tilde{D}_2^l(T) > C_2^l(T), \quad \text{(A10)}$$

and all users at $T^e \le T < T^l$ choose technology C. If $T > T^c + \frac{2e^{-r(T^l-T)}-1}{r}$, $\hat{s}_C(T) = 0$ and $C_2^l(T) > D_2^l(T)$, and all users choose technology C. □

Welfare Calculation

The social welfare in the scenario without subsidies equals

(A11)
$$W(T^c) = \frac{1}{r^3}\left(2be^{rT^c} + \left(ae^{rT^c} - \epsilon_D\left(e^{rT^c} - (1-p)e^{r(T^c-T^l)} - pe^{r(T^c-T^e)}\right)\right)r\right).$$

The expected social welfare for the group using technology D equals

$$\begin{aligned}
W_{D_{\hat{s}}}(T^c) =& p \cdot \int_0^{T^c} \left(\int_t^{T^c} [a + b \cdot \tau - \epsilon_D] \cdot e^{-r(\tau - t)}\, d\tau + \right. \\
& \int_{T^c}^{T^e} [a + b \cdot T^c - \epsilon_D] \cdot e^{-r(\tau - t)}\, d\tau + \\
& \left. \int_{T^e}^{\infty} [a + b(\tau - (T^e - T^c) - \epsilon_D] \cdot e^{-r(\tau - t)}\, d\tau \right) e^{-r(t - T^c)} dt \\
& + (1-p) \cdot \int_0^{T^c} \left(\int_t^{T^c} [a + b \cdot \tau - \epsilon_D] \cdot e^{-r(\tau - t)}\, d\tau + \right. \\
& \int_{T^c}^{T^l} [a + b \cdot T^c - \epsilon_D] \cdot e^{-r(\tau - t)}\, d\tau \\
& \left. + \int_{T^l}^{\infty} [a + b(\tau - (T^l - T^c) - \epsilon_D] \cdot e^{-r(\tau - t)}\, d\tau \right) e^{-r(t - T^c)} dt
\end{aligned}$$

(A12)

$$= \frac{1}{r^3} \left((ar - \epsilon_D r + 2b)(e^{rT^c} - 1) - bT^c r (2 - p e^{r(T^c - T^e)} - (1-p) e^{r(T^c - T^l)}) \right).$$

The expected social welfare for the group using technology C equals

$$\begin{aligned}
W_{C_{\hat{s}}}(T^c) =& p \cdot \int_{T^c}^{T^e} \left(\int_t^{T^e} [a + b(\tau - T^c) - \epsilon_C] e^{-r(\tau - t)}\, d\tau \right. \\
& \left. + \int_{T^e}^{\infty} [a + b(T^e - T^c) - \epsilon_C] e^{-r(\tau - t)}\, d\tau \right) e^{-r(t - T^c)} dt \\
& + (1-p) \cdot \int_{T^c}^{T^l} \left(\int_t^{T^l} [a + b(\tau - T^c) - \epsilon_C] e^{-r(\tau - t)}\, d\tau \right. \\
& \left. + \int_{T^l}^{\infty} [a + b(T^l - T^c)] e^{-r(\tau - t)}\, d\tau \right) e^{-r(t - T^c)} dt \\
=& \frac{1}{r^3} \left((ar - \epsilon_C r + 2b) \left(1 - (1-p) e^{r(T^c - T^l)} - p e^{r(T^c - T^e)} \right) \right. \\
& \left. - 2br \left((1-p)(T^l - T^c) e^{r(T^c - T^l)} + p (T^e - T^c) e^{r(T^c - T^e)} \right) \right). \quad \text{(A13)}
\end{aligned}$$

The expected social welfare for the group using technology B equals

$$\begin{aligned}
W_{B_{\hat{s}}}(T^c) =& p \cdot \int_{T^e}^{\infty} \left(\int_t^{\infty} [a + b(\tau - (T^e - T^c)) \cdot e^{-r(\tau - t)}\, d\tau \right) e^{-r(t - T^c)} dt \\
& + (1-p) \cdot \int_{T^l}^{\infty} \left(\int_t^{\infty} [a + b(\tau - (T^l - T^c))] \cdot e^{-r(\tau - t)}\, d\tau \right) e^{-r(t - T^c)} dt \\
=& \frac{(ar + b(2 + rT^c)) \left(p e^{r(T^c - T^e)} + (1-p) e^{r(T^c - T^l)} \right)}{r^3}. \quad \text{(A14)}
\end{aligned}$$

Proof of Proposition 2

To prove Proposition 2, we need the following lemma.

LEMMA 3: *If* $T^c < T^e < T^l$ *then* $1 - pe^{r(T^c - T^e)} - (1-p)e^{r(T^c - T^l)} > 0$.

Proof: Because $T^c < T^e < T^l$, it holds that

$$e^{rT^e}(e^{rT^l} - e^{rT^c}) > pe^{rT^c}(e^{rT^l} - e^{rT^e})$$
$$\iff e^{r(T^e+T^l)} - e^{r(T^e+T^c)} > pe^{r(T^c+T^l)} - pe^{r(T^c+T^e)}$$

(A15) $$\iff e^{r(T^e+T^l)} - pe^{r(T^c+T^l)} - (1-p)e^{r(T^c+T^e)} > 0$$

and because $e^{-r(T^e+T^l)} > 0$, it follows that

(A16) $$e^{-r(T^e+T^l)}\left(e^{r(T^e+T^l)} - pe^{r(T^c+T^l)} - (1-p)e^{r(T^c+T^e)}\right) > 0$$

and, therefore, $1 - pe^{r(T^c-T^e)} - (1-p)e^{r(T^c-T^l)} > 0$ holds. □

We can now prove Proposition 2. Simple calculation shows

$$W_{\hat{s}} - W = \frac{1}{r^2}\Big[(\epsilon_D - \epsilon_C)(1 - pe^{r(T^c-T^e)} - (1-p)e^{r(T^c-T^l)})$$

(A17) $$-2b(T^c + p(T^e - 2T^c)e^{r(T^c-T^e)} + (1-p)(T^l - 2T^c)e^{r(T^c-T^l)})\Big]$$

and (by using Lemma 3) $W_{\hat{s}} - W > 0$ holds if and only if

(A18) $$\epsilon_D - \epsilon_C > \frac{2b[T^c + p(T^e - 2T^c)e^{r(T^c-T^e)} + (1-p)(T^l - 2T^c)e^{r(T^c-T^l)})]}{1 - pe^{r(T^c-T^e)} - (1-p)e^{r(T^c-T^l)}},$$

as stated in the Proposition.□

Proof of Corollary 1

(A19) $$\frac{\partial\tilde{\epsilon}}{\partial b} = \frac{2[T^c + p(T^e - 2T^c)e^{r(T^c-T^e)} + (1-p)(T^l - 2T^c)e^{r(T^c-T^l)})]}{1 - pe^{r(T^c-T^e)} - (1-p)e^{r(T^c-T^l)}}$$

is (using Lemma 3 for the denominator's positiveness) positive if and only if

$$T^c + p(T^e - 2T^c)e^{r(T^c-T^e)} + (1-p)(T^l - 2T^c)e^{r(T^c-T^l)}) > 0.$$

Because $T^l > T^c$, it holds that

(A20) $$(1-p)T^l e^{r(T^c-T^l)} > (1-p)T^c e^{r(T^c-T^l)}.$$

Because $T^c < T^e$, it holds that $e^{r(T^c-T^e)} < 1$ and therefore

(A21) $$T^c(1 - e^{r(T^c-T^l)}) > T^c(e^{r(T^c-T^e)} - e^{r(T^c-T^l)}) > pT^c(e^{r(T^c-T^e)} - e^{r(T^c-T^l)})$$

Because $T^c < T^e$, it holds that

$$p(T^e - T^c)e^{r(T^c - T^e)} > 0. \tag{A22}$$

Summarizing the results in

$$\begin{aligned}
&(1-p)T^l e^{r(T^c-T^l)} + T^c(1-e^{r(T^c-T^l)}) + p(T^e - T^c)e^{r(T^c-T^e)} \\
&> (1-p)T^c e^{r(T^c-T^l)} + pT^c(e^{r(T^c-T^e)} - e^{r(T^c-T^l)}) \\
&\iff \\
&T^c + p(T^e - 2T^c)e^{r(T^c-T^e)} + (1-p)(T^l - 2T^c)e^{r(T^c-T^l)} > 0.
\end{aligned} \tag{A23}$$

Therefore, $\partial\tilde{\epsilon}/\partial b > 0$ holds. □

Proof of Corollary 2

(A24)

$$\frac{\partial\tilde{\epsilon}}{\partial r} = -\frac{2be^{-r(T^e+T^l-T^c)}\left(-e^{rT^c}(1-p)p(T^e-T^l)^2 + e^{rT^l}p(T^e-T^c)^2 + e^{rT^e}(1-p)(T^l-T^c)^2\right)}{(1-pe^{r(T^c-T^e)} - (1-p)e^{r(T^c-T^l)})^2}$$

Because the denominator, $e^{-r(T^e+T^l-T^c)}$, and b are positive,

$$\frac{\partial\tilde{\epsilon}}{\partial r} \gtreqqless 0 \tag{A25}$$

if and only if

$$-e^{rT^c}(1-p)p(T^e-T^l)^2 + e^{rT^l}p(T^e-T^c)^2 + e^{rT^e}(1-p)(T^l-T^c)^2 \lesseqqgtr 0. \tag{A26}$$

Because

$$e^{rT^c}(1-p)p(T^e-T^l)^2 < e^{rT^e}(1-p)(T^e-T^l)^2 < e^{rT^e}(1-p)(T^c-T^l)^2 \tag{A27}$$

and $e^{rT^l}p(T^e-T^c)^2 > 0$

$$-e^{rT^c}(1-p)p(T^e-T^l)^2 + e^{rT^l}p(T^e-T^c)^2 + e^{rT^e}(1-p)(T^l-T^c)^2 > 0. \tag{A28}$$

Therefore, $\partial\tilde{\epsilon}/\partial r < 0$ holds. □

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