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

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Abstract

This article shows that in the presence of environmental externalities, it may be welfare enhancing to overcome a technological lock-in by a dead-end technology through governmental intervention. It is socially desirable to subsidize a dead-end technology if its environmental externality is small relative to the one of the established technology, if the installed base and/or the strength of the network effect is small and if future generations matter. Applying our results to the private transport sector, governments promoting alternatives to gasoline-driven vehicles have to be aware of these opposing welfare effects.

JEL: O33; L92; Q55

Key words: environmental externalities, network effects, private transport, technological change

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1 Introduction

The automobile industry is developing several alternatives for the established petrol-driven internal combustion engine, for example, fuel cell, battery-driven electro motor, or biofuel-driven engines. Up to now, none of these alternative power trains have entered the mass market. Since the usability of a vehicle depends on the network of service stations, there is a large lock-in effect that favors the established technology. Even if some of the new technologies enter the market and one of them becomes the dominant technology, then it can be entirely replaced by another one at a later time. Likewise, at the end of the nineteenth century, steam- and battery-driven vehicles dominated the infant automobile market before the internal combustion engine succeeded. Therefore, even if the advantages of a new technology are large, users may not abandon the old technology and switch to the new technology when they fear that the new technology is a dead-end technology.

Many governments, such as the German, committed to reduce anthropogenic greenhouse gases. Since the transport sector is one of the largest producers of greenhouse gases, they try to reduce emissions from vehicles. In order to reach the aim of a reduction of 20 percent of greenhouse gas emissions up to 2020, they advocate green technologies. Since a Pigou tax that internalizes the external effect does not solve the lock-in advantage of the traditional technology, they consider subsidizing vehicles with an alternative or greener technology. However, subsidizing a dead-end technology reduces the utility that users get from the established one by destroying an established network of service stations.

This article deals with the interaction of service station networks, greenhouse gas emissions, and uncertain technological progress by answering the following question: Is it sensible to subsidize a green technology even if we know that it is a dead-end technology, or is it preferable to just wait for the better technology? By taking external environmental effects as well as network effects into account, we identify the pre-conditions for welfare-enhancing subsidies of a dead-end technology. The external environmental effect arises from emitting greenhouse gases, here short-living ones such as methane. Using a less polluting technology always reduces the external effect and, therefore, deserves subsidies. However, there is an opposing network effect. To use a vehicle, the consumer depends on filling and other service stations. Since the utility of an automobile user depends on the density of a service infrastructure and the density of service stations depends on the numbers of users, network effects do play a role. Subsidizing consumers into a dead-end technology reduces the utility of all consumers in the old network.

Our methodical analysis relates to the literature of the economics of networks (Economides, 1996; Birke, 2009). In particular, our model is based on the work of Farrell and Saloner (1986) and follows Sartzetakis and Tsigaris (2005). Farrell and Saloner (1986) show that due to an installed base, network effects can lead to excess inertia; thus, a superior technology is not adopted. Sartzetakis and Tsigaris (2005) amend the aspect of environmental externalities and apply the model to the automobile sector. Although they analyze two technologies, they do not consider dead-end technologies. Further, they are identifying policies to internalize the external effect. We are assuming that a complete internalization of the external environmental effect is not possible and instead search for a second-best policy.

Our analysis is based on the wide range of literature on the technological transition to alternative-fuel vehicles (Nishihara, 2010; Köhler et al., 2010; Schneider et al., 2004; Schwoon, 2007; Struben and Sterman, 2008). Some authors also take environmental externalities into account. Internalizing environmental and network externalities, Conrad (2009) shows the optimal path of investment chosen by the firm. Similar to Sartzetakis and Tsigaris (2005), the author searches for an optimal policy that we reckon as impossible. Modeling the adoption decision of consumers and filling station owners, Greaker and Heggedal (2010) conclude that the government should internalize the environmental externalities via taxation. Due to a difficulty in determining whether there is a lock-in situation or not, the authors reject governmental intervention to internalize the network externality. We state the existence of a lock-in situation, and, therefore, claim governmental action. Others only consider network effects while analyzing different aspects within the adoption process. For example, Bento (2010) focuses on the consumers' decision to buy a hybrid or a fuel cell vehicle. He stresses the role of network effects in the players' decisions. He finds a risk of locking-in another technology within the transitory process, whereas we stress the risk of not using a welfare-enhancing dead-end technology.

2 One Green Technology

As in Sartzetakis and Tsigaris (2005), we assume that one infinitely lived automobile user per time unit continuously arrives at the market. All users inelastically demand a single car. No buyer of a car demands a different car in the future. Users of the current technology D (dirty), here gasoline-driven vehicles, emit the environmental externality ϵ_D, that is, greenhouse gases with a short lifetime such as methane. A benefit a is generated from the technology's general characteristic to meet mobility. Further, to use the technology, frequent use of service stations is necessary, and users prefer a dense net of service stations. As the number of users of a given technology increases, so does the number of service stations for this particular technology. We assume that one service station opens 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 of D.

The technology D enters the market at period $T_0 = 0$. Further, we assume that the price of a car is normalized to zero. The net present value of the benefit (NPV) of a new user arriving at time T if D is used up to infinity is

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

$$= \frac{a + b \cdot T}{r} + \frac{b}{r^2}, \tag{2}$$

with r being the discount factor.

At time $T^* > 1/r$, a new technology, for example, electric mobility, is ready for the market. Since it emits $\epsilon_C < \epsilon_D$ less than the technology D, we call it clean technology C. We assume that the new technology and the old technology are equally well designed to serve the mobility needs of the users. However, due to $D's$ already installed base $T^* - T_0 = T^*$ at time $T^* > 1/r$, rational new users, who do not consider the external benefit, do choose the old technology D, known as excess inertia (Farrell and Saloner, 1986).[1]

The government may induce a switch toward the clean technology from T^* 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 a policy and the subsidy is successful in influencing all new users at $T \geq T^*$ to choose C. For each user entering the market at $T > T^*$, there already exists a network of the size $T - T^*$. The NPV of a user at time $T \geq T^*$ if C is used up to infinity by all the following users equals

$$C(T) = \int_T^\infty [a + b(t - T^*)]e^{-r(t-T)}\, dt \tag{3}$$

$$= \frac{a + b\,(T - T^*)}{r} + \frac{b}{r^2}. \tag{4}$$

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

$$\tilde{D}(T) = \int_T^\infty [a + b(T^* - T_0)]e^{-r(t-T)}\, dt \tag{5}$$

$$= \frac{a + b \cdot T^*}{r}. \tag{6}$$

Figure 1 shows the network's growth for both technologies over time. The thick line describes the path of the D-network. It grows from $T_0 = 0$ until $T^* = 1$, then it stops growing. The dashed line outlines the D-path, if the second technology does not appear. The thin line shows the path of the C-network. Starting at $T^* = 1$, it has the same size such as technology D at $2T^* = 2$. After that, it is larger than the D-network.

[1] If $T^* < 1/r$, then buying C is optimal if users assume that all new users will buy C also. Therefore, no subsidy is needed. That means, $T^* = 1/r$ is the critical installed base. If the network exceeds this size, then there is a lock-in that cannot be overcome without governmental intervention (Arthur, 1989; David, 1985). In other related work, this is called critical mass (Witt, 1997).

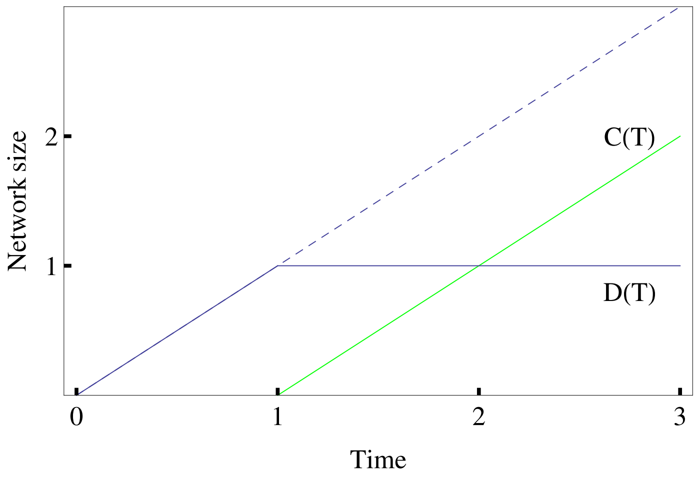

Figure 1: The one green technology scenario

Lemma 1 *If the government pays the subsidy*

$$\hat{s}(T) = \begin{cases} \frac{b(2T^*-T)}{r} - \frac{b}{r^2}, & \textit{for } T^* \leq T \leq 2T^* - \frac{1}{r} \\ 0, & \textit{for } T \geq 2T^* - \frac{1}{r} \end{cases}, \tag{7}$$

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

Proof: See Appendix.

As long as $\tilde{D}(T) > C(T)$, the government has to pay the subsidy $\hat{s}(T)$. It compensates the early C-users, because they cannot use the installed larger network of technology D. This is calculated by $\frac{b(2T^*-T)}{r}$. Without this subsidy, it is not rational to choose the cleaner technology C. Since the D-network stops growing when then C-network starts growing, the compensation for the early C-users can be reduced each period until $2T^* - \frac{1}{r}$; therefore, we have to subtract $\frac{b}{r^2}$. After this time the government can stop paying it.

Proposition 1 *Subsidizing the* C *technology is welfare enhancing if* $\epsilon_D - \epsilon_C \geq 2bT^*$*.*

Proof: See Appendix.

Proposition 1 shows that the government can enhance social welfare by overcoming lock-in, thus by subsidizing the new green technology C. The condition states the opposing effect of environmental benefit and network effect. The use of the less emitting technology C reduces environmental externalities and, therefore, enhances welfare. On the other hand, since the utility of an automobile user depends on the density of a service infrastructure, using technology C reduces welfare, because it is not compatible to the installed D-network. Therefore, subsidizing technology C is welfare enhancing, if the environmental benefit of using the less emitting technology C is larger than the benefit of using the installed network.

3 Two Green Technologies

We now consider the case that, since technologies improve, at some time $T^{**} > 2T^* - 1/r$ in the future, there will be a green (better) technology B, which is compatible to the old technology D but has a smaller external effect $\epsilon_B = 0$ than C, for example, a new generation of biofuels. Is it still sensible to subsidize the technology C even if we know that it is a dead-end technology, or is it better to just wait for the better technology and not to use or subsidize C?

To answer this question, we create a scenario where from T^* to T^{**} all users choose C. Since $T^* > 1/r$, the D-network has reached its critical size; thus, there is a lock-in situation. Therefore, the new users only choose C because of subsidies that are paid by the government. Again, we assume that the government is able to commit to its policy. Setting $T_0 = 0$, the networks of D and the subsidized C have the same size at $2T^*$. If $T^{**} < 2T^*$, then the C-network is smaller than the D-network at T^{**} and all later arriving users buy B. The government stops supporting C. It is unclear as to when the new technology is ready for the market. With a probability $0 < p < 1$, the B-technology enters the market at T^e. To simplify calculations, we set $T^e = T^{**} = 2T^* - \delta$, with $0 < \delta < 1/r$. [2]

Figure 2 shows the network's growth for the three technologies in such a scenario. The fat line describes the path of the D-network. Here, it increases from $T_0 = 0$ until $T^* = 2$. Then, it stops growing for the period $T^* = 2$, when C is chosen, until $2T^* - \delta = 3$, when B enters the market. Then, it continues to

[2]Since $T^{**} = 2T^* - \delta > 2T^* - 1/r$, it has to hold $\delta < 1/r$.

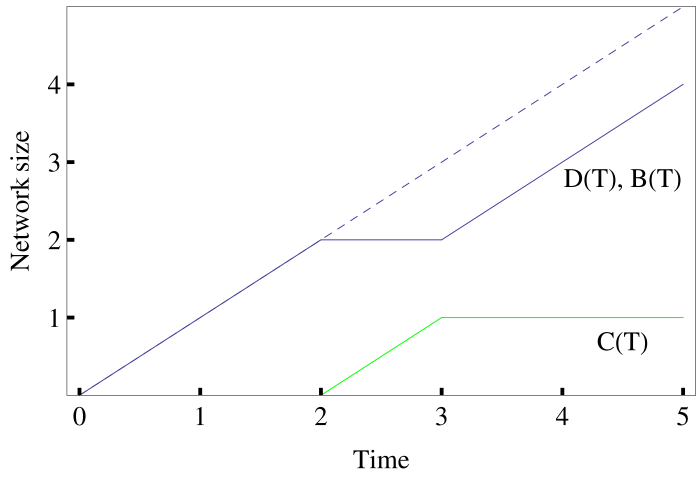

Figure 2: The scenario for $T^{**} = 2T^* - \delta$

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 $T^* = 2$ until $2T^* - \delta = 3$. After that, it remains at the size reached at $2T^* - \delta = 3$.

However, if $T^{**} > 2T^*$, then the subsidized network of C is larger than the D-network. Even in this case, rational users switch to the B-technology without subsidies, because $\delta < 1/r$. [3] Therefore, the government has to subsidize C until B arrives. With the probability $1 - p$, technology B appears at $T^l > T^e$. For simplification, we set $T^l = T^{**} = 2T^* + \delta$.

Figure 3 shows the network's evolution of the three technologies in this scenario. Here, technology B appears at $2T^* + \delta = 5$. Therefore, the C-network can exceed the size of the D-network at $T = 4$. It stops growing when B enters the market, and since the $D - B$ network continues to expand, the later exceeds the former at $T = 6$.

As just seen, since B arrives at a future period, the NPV for the users of D changes as well. It does not end in T^*, but continues to grow in T^{**} when B appears. To calculate the NPV, we also have to take into account that this can happen at two different points in time. Therefore, the NPV for one user of the

[3] If $\delta > 1/r$, then the government also has to subsidize B.

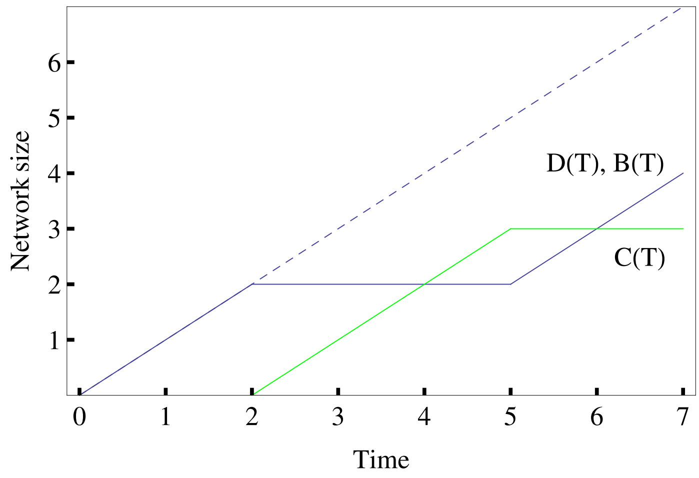

Figure 3: The scenario for $T^{**} = 2T^* + \delta$

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

$$D_2(T) = \int_T^{T^*} [a + b \cdot t] e^{-r(t-T)}\, dt \tag{8}$$

$$+ p \left(\int_{T^*}^{2T^*-\delta} [a + b \cdot T^*] e^{-r(t-T)}\, dt \right. \tag{9}$$

$$\left. + \int_{2T^*-\delta}^{\infty} [a + b(t - (T^* - \delta))] e^{-r(t-T)}\, dt \right) \tag{10}$$

$$+ (1-p) \left(\int_{T^*}^{2T^*+\delta} [a + b \cdot T^*] e^{-r(t-T)}\, dt \right. \tag{11}$$

$$\left. + \int_{2T^*+\delta}^{\infty} [a + b(t - (T^* + \delta))] e^{-r(t-T)}\, dt \right) \tag{12}$$

$$= \frac{a + b \cdot T}{r} + \frac{b(1 - e^{-r(T^*-T)} + p \cdot e^{-r(2T^*-\delta-T)} + (1-p) \cdot e^{-r(2T^*+\delta-T)})}{r^2}. \tag{13}$$

From T^* onward in our scenario, all users choose technology C. Due to the arrival of technology B, their benefit also changes. Now, they are ending in a dead network. When this happens depends on the probability p. The NPV for one of these users appearing at $T^* < T < T^{**}$ equals

$$C_2(T) = p\left(\int_T^{2T^*-\delta} [a + b(t - T^*)] \cdot e^{-r(t-T)}\, dt \right. \tag{14}$$

$$\left. + \int_{2T^*-\delta}^{\infty} [a + b(T^* - \delta)] \cdot e^{-r(t-T)}\, dt \right) \tag{15}$$

$$+ (1-p)\left(\int_T^{2T^*+\delta} [a + b(t - T^*)] \cdot e^{-r(t-T)}\, dt \right. \tag{16}$$

$$\left. + \int_{2T^*+\delta}^{\infty} [a + b(T^* + \delta)] \cdot e^{-r(t-T)}\, dt \right) \tag{17}$$

$$= \frac{a + b(T - T^*)}{r} + \frac{b(1 - p \cdot e^{-r(2T^*-\delta-T)} - (1-p) \cdot e^{-r(2T^*+\delta-T)})}{r^2}. \tag{18}$$

The NPV of the user choosing D at $T^* < T < T^{**}$, if the last user of D was at time T^*, equals

$$\tilde{D}_2(T) = \frac{a + b \cdot T^*}{r} + \frac{b(p \cdot e^{-r(2T^*-\delta-T)} + (1-p) \cdot e^{-r(2T^*+\delta-T)})}{r^2}. \tag{19}$$

When technology B appears, the government will stop paying subsidies to the C-users. Therefore, the government has to compensate the users of C not only for not using the D-network, but also for ending in the dead network. Otherwise they would choose D.

Lemma 2 *If the government pays*

$$\hat{s}_C(T) = \frac{b(2T^* - T)}{r} - \frac{b\left(1 - 2p \cdot e^{-r(2T^*-\delta-T)} - 2(1-p) \cdot e^{-r(2T^*+\delta-T)}\right)}{r^2} \tag{20}$$

from T^* till T^{**}, then all users entering at $T \geq T^*$ choose C.[4]

Proof: See Appendix.

As long as $\tilde{D}_2(T) > C_2(T)$, the government has to pay the subsidy $\hat{s}_C(T)$. This subsidy can be interpreted as in section 2. It compensates the C-users for using a small network, which is calculated by $\frac{b(2T^*-T)}{r}$. Since the C-network grows, whereas the D-network remains constant, the subsidy can be reduced each period.

[4]If $\delta \geq \frac{ln(2)}{r}$, then all users choose C if the government pays $\hat{s}_C(T)$ from T^* to $T \leq 2T^* - \frac{1+W(-2 \cdot e^{-1-r\delta})}{r}$ and from $T \geq 2T^* - \frac{1+W_{-1}(-2 \cdot e^{-1-r\delta})}{r}$ till T^{**}.

This effect is described by $-\frac{b}{r^2}$. However, the C-users end in a dead network after T^{**}. The rest of the second term, $\frac{2p \cdot e^{-r(2T^*-\delta-T)}+2(1-p)\cdot e^{-r(2T^*+\delta-T)}}{r^2}$, can be interpreted as the compensation for it. Again, the government decides at T^*, so the future payoffs are discounted by r.

At T^{**}, technology B enters the market. Since $\delta < 1/r$, technology B does not have to be subsidized. Rational new users choose B, if they expect future users are doing the same.

Welfare analysis The welfare W is defined as the sum of consumer rent as sum of the utility from using the technology C or D or B (which is free of charge) minus the external effect from using the technologies. The subsidies $\hat{s}_C$ are payed by the government and received by the consumers and, therefore, does change welfare only indirectly by changing the type of technology used. Analyzing the change in welfare due to the technological change, we have to look at the different paths depending on the technology chosen.

Without subsidies, technology C cannot achieve in the market because of the network externalities resulting from the service infrastructure of technology D. New users will choose D from T^* on until technology B enters the market. Then, they choose the better technology B. We assume ϵ-altruism.

Social welfare without subsidies equals

$$W = p \cdot \left(\int_0^{2T^*-\delta} \int_t^{\infty} [a + b \cdot \tau - \epsilon_D] \cdot e^{-r(\tau - T^*)} \, d\tau dt + \right. \tag{21}$$

$$\left. \int_{2T^*-\delta}^{\infty} \int_t^{\infty} [a + b \cdot \tau] \cdot e^{-r(\tau - T^*)} \, d\tau dt \right) + \tag{22}$$

$$(1-p) \cdot \left(\int_0^{2T^*+\delta} \int_t^{\infty} [a + b \cdot \tau - \epsilon_D] \cdot e^{-r(\tau - T^*)} \, d\tau dt + \right. \tag{23}$$

$$\left. \int_{2T^*+\delta}^{\infty} \int_t^{\infty} [a + b \cdot \tau] \cdot e^{-r(\tau - T^*)} \, d\tau dt \right), \tag{24}$$

which is the reference scenario in the following analysis. As just described, in this scenario, all users choose technology D with the external effect ϵ_D from $T_0 = 0$ until T^{**} and from T^{**} on, they choose B with the external effect $\epsilon_B = 0$. The first term calculates the welfare for the case that B arrives at the early time T^e, whereas the second term calculates for the case that B arrives at the later T^l.

Social welfare with subsidies equals

$$W_{\hat{s}} = W_{D_{\hat{s}}} + W_{C_{\hat{s}}} + W_{B_{\hat{s}}}, \tag{25}$$

which is the alternative scenario for the government. In this scenario, we have three types of users differing in the technology they are using. The first group enters the market before T^* so that they have to take technology D. The second group is the one choosing the C-technology, as they arrive at the later period from T^* to T^{**}. Finally, the users entering the market from T^{**} on use technology B. To calculate the welfare for each of these groups, we also have to consider the two possible times for B to appear. The welfare for the groups is separately calculated as follows:

Social welfare for the group using technology D equals

$$W_{D_{\hat{s}}}(T^*) = p \cdot \int_0^{T^*} \left(\int_t^{T^*} [a + b \cdot \tau - \epsilon_D] \cdot e^{-r(\tau - T)}\, d\tau + \right. \tag{26}$$

$$\int_{T^*}^{2T^* - \delta} [a + b \cdot T^* - \epsilon_D] \cdot e^{-r(\tau - T)}\, d\tau + \tag{27}$$

$$\left. \int_{2T^* - \delta}^{\infty} [a + b(\tau - (2T^* - \delta - T^*) - \epsilon_D] \cdot e^{-r(\tau - T)}\, d\tau \right) dt \tag{28}$$

$$+ (1 - p) \cdot \int_0^{T^*} \left(\int_t^{T^*} [a + b \cdot \tau - \epsilon_D] \cdot e^{-r(\tau - T)}\, d\tau + \right. \tag{29}$$

$$\int_{T^*}^{2T^* + \delta} [a + b \cdot T^* - \epsilon_D] \cdot e^{-r(\tau - T)}\, d\tau \tag{30}$$

$$\left. + \int_{2T^* + \delta}^{\infty} [a + b(\tau - (2T^* + \delta - T^*) - \epsilon_D] \cdot e^{-r(\tau - T)}\, d\tau \right) dt. \tag{31}$$

$$\tag{32}$$

Social welfare for the group using technology C equals

$$W_{C_{\hat{s}}}(T^*) = p \cdot \int_{T^*}^{2T^*-\delta} \left(\int_{t}^{2T^*-\delta} [a + b(\tau - T^*) - \epsilon_C] e^{-r(\tau - T)} \, d\tau \right. \tag{33}$$

$$\left. + \int_{2T^*-\delta}^{\infty} [a + b(2T^* - \delta - T^*) - \epsilon_C] e^{-r(\tau-T)} \, d\tau \right) dt \tag{34}$$

$$+ (1-p) \cdot \int_{T^*}^{2T^*+\delta} \left(\int_{t}^{2T^*+\delta} [a + b(\tau - T^*) - \epsilon_C] e^{-r(\tau-T)} \, d\tau \right. \tag{35}$$

$$\left. + \int_{2T^*+\delta}^{\infty} [a + b(2T^* + \delta - T^*)] e^{-r(\tau-T)} \, d\tau \right) dt. \tag{36}$$

Social welfare for the group using technology B equals

$$W_{B_{\hat{s}}}(T^*) = p \cdot \int_{2T^*-\delta}^{\infty} \int_{t}^{\infty} [a + b(\tau - (2T^* - \delta) - T^*) \cdot e^{-r(\tau - T^*)} \, d\tau dt \tag{37}$$

$$+ (1-p) \cdot \int_{2T^*+\delta}^{\infty} \int_{t}^{\infty} [a + b(\tau - (2T^* + \delta) - T^*)] \cdot e^{-r(\tau - T^*)} \, d\tau dt. \tag{38}$$

At time T^*, the government has to decide whether to pay subsidies or not. Since the government maximizes social welfare, it should subsidize C if $W \leq W_{\hat{s}}$ holds.

Proposition 2 *If*

$$\epsilon_D - \epsilon_C > \frac{-2b[T^* \cdot e^{r(T^*+\delta)} + (1 - p - p \cdot e^{2r\delta})\delta]}{1 - p - e^{r(T^*+\delta)} + p \cdot e^{2r\delta}} = \tilde{\epsilon}, \tag{39}$$

then $W < W_{\hat{s}}$*, and it is welfare enhancing to subsidize the dead-end technology.*

Proof: See Appendix.

Proposition 2 shows that even if technology C is a dead-ending one, it can be socially desirable to subsidize its usage to overcome lock-in. By subsidizing technology C, on the one hand, social welfare enhances due to the reduction of greenhouse gas emissions. However, on the other hand, subsidizing C reduces social welfare as it is not compatible to the installed D-network. The consequence of choosing technology C is the existence of two incompatible networks. Therefore, the welfare-enhancing government should subsidize the dead-end technology C, only if the reduction in the external effect exceeds the benefit of compatibility.

Comparative statics The size of the critical $\tilde{\epsilon}$ depends on distinct factors.

Corollary 1 *It holds* $\frac{\delta\tilde{\epsilon}}{\delta b} > 0$.

Proof: See appendix.

The parameter b describes the strength of the network effect. If the network effect is large, then the larger has to be $\Delta\epsilon$ so that $W_s > W$ holds. This describes the relation between the benefit loss of incompatibility to the D-network and the environmental benefit of using the cleaner technology C. If the network benefit from the installed D-network is large, then the environmental benefit also has to be large. Otherwise, it is not welfare enhancing to support the cleaner technology.

Corollary 2 *It holds* $\frac{\delta\tilde{\epsilon}}{\delta r} < 0$.

Proof: See appendix.

The discounting factor r describes the evaluation of the future. If the future is valued a lot, then the smaller can be $\Delta\epsilon$, and $W_s > W$ still holds. With each future period, the C-network grows, whereas the size of the D-network remains constant. That means, the benefit loss of incompatibility abates over time, whereas the emissions from the D-technology arise each period at a constant level. Thus, the relative benefit of using the cleaner technology grows each period. A large r values this benefit higher. Therefore, it is socially desirable to support C for smaller $\Delta\epsilon$.

Corollary 3 *It holds* $\frac{\delta\tilde{\epsilon}}{\delta T^*} > 0$.

Proof: See appendix.

The later technology C enters the market, the larger $\Delta\epsilon$ has to be so that $W_s > W$ holds. If C arrives later in the market, then the installed base of technology D is large. Therefore, the benefit loss of not using this network is large. As follows, the environmental benefit of using C has to be large, that means, $\Delta\epsilon$ also has to be large.

Our results can be applied to the case of electric mobility as the most subsidized alternative to gasoline-driven vehicles. Corollary 1 and 3 state that intervention when the network effect is strong, for example, because the installed base is large, is justified only if the environmental benefit is significant. Up to now, there exists no appropriate network of filling and service stations for electric cars. This means that the network effect of the already installed service stations network for gasoline-driven cars is large. Therefore, the greenhouse gas reduction of battery-driven mobility also has to be large. Otherwise, a governmental intervention would not enhance welfare. Considering the German mix of electricity production, emitting on average 563g carbon dioxide per kWh, it would hardly enhance social welfare to subsidize this technology. However, if the electricity could be gained from low greenhouse gas emitting energy sources such as wind or solar, then the usage of battery driven-vehicles would significantly reduce greenhouse gas emission. Further, we assumed (in order to stress our argument) a dead-end technology, which means that it is already known that there is a better technology available in the future. Up to now, it is not clear at all whether or not electric-driven cars are a dead-end technology. The subsidization of an open-end technology, see proposition 1, is welfare enhancing even if the ecological effect is much smaller. As corollary 2 states, the decision whether to subsidize electric mobility also depends on the value of the future. This connection is deeply discussed by Stern (2006) and Nordhaus (2007).

4 Conclusion

In the presence of environmental externalities, it can be welfare enhancing to overcome a technological lock-in via governmental intervention. As our model shows, this may also hold for a dead-end technology that appears within a process of technological transition. Within our model, there exists an opposing effect between environmental benefits of using a cleaner technology and the losses of incompatible networks. The reduction of environmental externalities enhances welfare, whereas the network incompatibility reduces the utility for all consumers. The important parameters within the analysis are the difference of the environmental externalities, the strength of the network effect, and the size of the installed base. Besides, the governmental decision whether to subsidize or not also depends on the value of future payoffs; thus, the discount factor. It is desirable to subsidize the dead-end technology if its environmental externality is small relative to the one of the established technology, if the installed base is small, and/or if the strength of the network effect is small. If future generations matter, which means, if consumers' and politicians' discounting of future payoffs is small, then they subsidize a green dead-end technology.

Appendix

Proof of Lemma 1

As long as $\tilde{D}(T) > C(T)$, the government has to pay a subsidy $\hat{s}$. Since the network of C grows with each new user, the subsidy can be reduced with time. Let (as in 7)

$$\hat{s}(T) = \begin{cases} \frac{b(2T^*-T)}{r} - \frac{b}{r^2}, & \text{for } T^* \leq T \leq 2T^* - \frac{1}{r} \\ 0, & \text{for } T \geq 2T^* - \frac{1}{r} \end{cases}. \tag{40}$$

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

$$C(T) + \hat{s}(T) = \frac{a + b\,(T - T^*)}{r} + \frac{b}{r^2} + \frac{b\,(2T^* - T)}{r} - \frac{b}{r^2} \tag{41}$$

$$= \frac{a + b \cdot T^*}{r} = \tilde{D}(T), \tag{42}$$

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

Proof of Proposition 1

To proove proposition 1, we have to calculate the status quo welfare W_N for the scenario without subsidy

$$W_N = \int_0^\infty \int_t^\infty (a + b \cdot \tau - \epsilon_D) e^{-r(\tau - T)}\, d\tau\, dt \tag{43}$$

$$= \frac{(2b + (a - \epsilon_D) r) e^{rT^*}}{r^3} \tag{44}$$

and W_S, where the government pays subsidies according to lemma 1.

$$W_S = \int_0^{T^*} \left(\int_t^{T^*} [a + b \cdot \tau - \epsilon_D] e^{-r(\tau - T)}\, d\tau \right. \tag{45}$$

$$\left. + \int_{T^*}^\infty [a + b \cdot T^* - \epsilon_D] e^{-r(\tau - T)}\, d\tau \right) dt \tag{46}$$

$$+ \int_{T^*}^\infty \int_{T^*}^\infty [a + b(\tau - T^*) - \epsilon_C] e^{-r(\tau - T)}\, d\tau dt \tag{47}$$

$$= \frac{r(ae^{rT^*} - \epsilon_D(e^{rT^*} - 1) - \epsilon_C - 2bT^*) + 2bT^* e^{rT^*}}{r^3} \tag{48}$$

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

$$\frac{\epsilon_C - \epsilon_D + 2bT^*}{r^2} \leq 0 \Longleftrightarrow W_N - W_S \leq 0 \Longleftrightarrow W_N \leq W_S \tag{49}$$

holds. □

Proof of Lemma 2

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

Let (as in 20)

$$\hat{s}_C(T) = \frac{b(2T^* - T)}{r} - \frac{b\left(1 - 2p \cdot e^{-r(2T^*-\delta-T)} - 2(1-p) \cdot e^{-r(2T^*+\delta-T)}\right)}{r^2}. \tag{50}$$

Since $\delta < \frac{ln(2)}{r}$,

$$\frac{b(2T^* - T)}{r} - \frac{b\left(1 - 2p \cdot e^{-r(2T^*-\delta-T)} - 2(1-p) \cdot e^{-r(2T^*+\delta-T)}\right)}{r^2} > 0 \Longleftrightarrow \tag{51}$$

$$\tilde{D}_2(T) - C_2(T) > 0 \Longleftrightarrow \tilde{D}_2(T) > C_2(T), \tag{52}$$

and all users at $T \geq T^*$ choose C. □

Proof of Proposition 2

To proove proposition, 2 we need the following lemma.

Lemma 3 *For* $0 < p < 1$, $\frac{-2b[T^* \cdot e^{r(T^*+\delta)} + (1-p-p \cdot e^{2r\delta})\delta]}{1-p-e^{r(T^*+\delta)}+p \cdot e^{2r\delta}} > 0$ *holds.*

Proof: Since $\frac{e^{r(T^*+\delta)}-1}{e^{2r\delta}-1} > 1$ and as per assumption, $0 < p < 1$

$$1 - p - e^{r(T^*+\delta)} + p \cdot e^{2r\delta} < 0$$

always holds. Since $\frac{T^* \cdot e^{r(T^*+\delta)}+\delta}{(e^{2r\delta})\delta} > 1$ and as per assumption, $0 < p < 1$

$$T^* \cdot e^{r(T^*+\delta)} + (1 - p - p \cdot e^{2r\delta})\delta > 0$$

always holds. Therefore, since $-2b < 0$,

$$\frac{-2b[T^* \cdot e^{r(T^*+\delta)} + (1 - p - p \cdot e^{2r\delta})\delta]}{1 - p - e^{r(T^*+\delta)} + p \cdot e^{2r\delta}} > 0$$

holds. □

Now, we can proove proposition 2.

Proof: Since $\frac{e^{-r(2+\delta)}}{r^2} > 0$ and $\epsilon_D - \epsilon_C > \frac{-2b[T^* \cdot e^{r(T^*+\delta)} + (1-p-p \cdot e^{2r\delta})\delta]}{1-p-e^{r(T^*+\delta)}+p \cdot e^{2r\delta}} > 0$,

$$\frac{e^{-r(2+\delta)}}{r^2}\Big[(\epsilon_D - \epsilon_C)(1 - p - e^{r(T^*+\delta)} + p \cdot e^{2r\delta}) \tag{53}$$

$$+2b(T^* \cdot e^{r(T^*+\delta)} + (1 - p - p \cdot e^{2r\delta})\delta)\Big] < 0 \Longleftrightarrow \tag{54}$$

$$W - W_{\hat{s}} < 0 \Longleftrightarrow W < W_{\hat{s}} \tag{55}$$

holds. □

Proof of Corollary 1

$$\frac{\delta\tilde{\epsilon}}{\delta b} = \frac{-2(T^* \cdot e^{r(T^*+\delta)} + (1 - p - p \cdot e^{2r\delta})\delta)}{1 - p - e^{r(T^*+\delta)} - p \cdot e^{2r\delta}} \tag{56}$$

Proof: See proof of Lemma 3.

Proof of Corollary 2

$$\frac{\delta\tilde{\epsilon}}{\delta r} = \frac{2b \cdot e^{r\delta}(-p(T^* - \delta)^2 \cdot e^{r(T^*+2\delta)} + (p-1)(-4p\delta^2 \cdot e^{r\delta} + (T^* + \delta)^2 \cdot e^{rT^*})}{(-1 + p + e^{r(T^*+\delta)} - p \cdot e^{2r\delta})^2} \tag{57}$$

Proof: Since $b > 0$,

$$\frac{2b \cdot e^{r\delta}}{(-1 + p + e^{r(T^*+\delta)} - p \cdot e^{2r\delta})^2} > 0. \tag{58}$$

Since $T^* > \delta$,

$$-p(T^* - \delta) \cdot e^{r(T^*+2\delta)} < 0, \tag{59}$$

and

$$(p-1)(T^{*2} \cdot e^{rT^*} - p\delta^2 \cdot e^{r\delta} + 2T^*\delta \cdot e^{rT^*} - 2p\delta^2 \cdot e^{r\delta} \tag{60}$$

$$+\delta^2 \cdot e^{rT^*} - p\delta^2 \cdot e^{r\delta}) < 0 \Longleftrightarrow \tag{61}$$

$$(p-1)(-4p\delta^2 \cdot e^{r\delta} + (T^* + \delta)^2 \cdot e^{rT^*}) < 0. \tag{62}$$

Therefore, $\frac{\delta\tilde{\epsilon}}{\delta r} < 0$ holds. □

Proof of Corollary 3

$$\frac{\delta\tilde{\epsilon}}{\delta T^*} = \frac{2b \cdot e^{r(T^*+\delta)}(e^{r(T^*+\delta)} + p(r(\delta - T^*) - 1) \cdot e^{2r\delta} + (p-1)(1 + r(T^* + \delta))}{(-1 + p + e^{r(T^*+\delta)} - p \cdot e^{2r\delta})^2} \tag{63}$$

Proof: Since $b > 0$,

$$\frac{2b \cdot e^{r(T^*+\delta)}}{(-1 + p + e^{r(T^*+\delta)} - p \cdot e^{2r\delta})^2} > 0. \tag{64}$$

Since

$$e^{r(T^*+\delta)} - 1 \geq p(e^{2r\delta} - 1) \Longleftrightarrow r \cdot e^{r(T^*+\delta)} \geq r - pr + pr \cdot e^{2r\delta} \Longleftrightarrow \tag{65}$$

$$\frac{\delta(e^{r(T^*+\delta)})}{\delta T^*} \geq \frac{\delta(-p((r(\delta - T^*) - 1) \cdot e^{2r\delta} + (p-1)(1 + r(T^* + \delta)))}{\delta T^*}, \tag{66}$$

and

$$\lim_{r,T^*,\delta \to 0} e^{r(T^*+\delta)} = 1$$

and

$$\lim_{r,T^*,\delta \to 0} -(p(r(\delta - T^*) - 1) \cdot e^{2r\delta} + (p-1)(1 + r(T^* + \delta))) = 1,$$

$$e^{r(T^*+\delta)} > -(p(r(\delta - T^*) - 1) \cdot e^{2r\delta} + (p-1)(1 + r(T^* + \delta))) \Longleftrightarrow \tag{67}$$

$$e^{r(T^*+\delta)} + p(r(\delta - T^*) - 1) \cdot e^{2r\delta} + (p-1)(1 + r(T^* + \delta)) > 0 \tag{68}$$

$$\tag{69}$$

holds.

Therefore, $\frac{\delta\tilde{\epsilon}}{\delta T^*} > 0$ holds. □

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