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The Path Dependent Road to Sustainable Personal Transport

Increasing returns economics and the lock-in and lock-out effects on the history and future of motorized transport

Master's Thesis

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Abstract

Personal mobility around the world today is dominated by the internal combustion engine and the oil industry. In fact, transportation is the economic sector that remains most monopolized by fossil fuels despite the international resolve to combat anthropogenic climate change solidified by the Paris Agreement in 2015. Furthermore, while many other economic sectors have begun to decarbonize, carbon emissions from transportation have actually been increasing in recent decades. This dissertation will explore why personal automotive transport has been so dependent on oil while more sustainable technologies have been widely available for over a century. An increasing returns economic model within a path dependency framework will be applied to analyze the historical development of the automobile from its beginnings until today, illuminating the multitude of factors which have culminated in the lock-in effect of gasoline-powered cars. The mechanisms by which competing technologies (electric vehicles and biofuels) were locked out from the market despite offering potential performance benefits will be assessed in parallel. Here, the novel concepts of *inherent lock-out* and *intentional lock-out* will be introduced to help provide a more concrete interpretation of the different causes of lock out in a technological market and how they can be broken. This thesis will focus on the experiences of the US and the EU with the personal automobile and how the societal institutions have developed around the new transportation system. The different political, economic, social, and institutional environments across the two populations will be explored with an emphasis on the policies in place for transport decarbonization. The same path dependency with increasing returns framework will then be applied to decipher the best road ahead for each government to achieve a sustainable, decarbonized personal transportation sector as quickly as possible.

Keywords
Climate change, sustainable transportation, energy transition, ethanol, biofuels, advanced biofuels, path dependency, carbon lock-in, lock-out effect, electric vehicles, increasing returns

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Chapter 1. Introduction

The cognitive wherewithal and physical dexterity to create tools - technology - is an all-empowering wonder of evolution exclusively bestowed upon man. This gift has actually, in a sense, become detrimental to the Darwinian process through which it arose. Technology has given humans the ability to exploit natural resources to an extent well beyond our corporeal means, which has in turn allowed us to dominate the food chain and even mitigate natural selection within our species through the miracle of medicine. To apply the institutionalist theory of path dependency, *homo sapiens* have established themselves as the *dominant design* of Earth-bound, terrestrial life. The species has interacted with the environment to create habitats conducive to its own survival and prosperity, generating positive feedback mechanisms supporting the sustenance and proliferation of human beings. Over time, as settlements are erected alongside infrastructure, this results in the lock-in of people to that habitat. This phenomenon, along with the aid of weaponized tools, also serves to lock out other species - or other groups of humans - which might pose a threat to the inhabitants' control of the territory. That is, until a competitor arrives who has developed the means to disrupt and replace the incumbent. These concepts will be explained and elaborated upon throughout this text, which will explore them in the analogous context of modern transportation systems, but it may prove enlightening for the reader to retain the above example and recognize that the challenges ahead are in fact rooted in human nature.

Transportation is one of the major manifestations of human ingenuity - from horseback to carriages to boats to steam engines to automobiles to airplanes to rocketships, mobility has been integral to the development of society. In fact, this facet of the human experience has served to define epochs of time - the Silk Road has become the enduring symbol of inter-cultural trade; the advent of large, durable seafaring vessels brought about the Age of Exploration; the Age of Steam introduced long distance travel by land and sea to the masses; the Age of Oil is directly tied to the popularization of the internal combustion engine; and the Space Race captured the imaginations of the world around, along with the military budgets of the world's two rising superpowers. Today more than ever, transportation also dictates our lives within modern society.

It lies at the core of our economy, enabling people to get to work and goods to reach consumers, and it empowers us to escape a lock-in to the microcosm in which we were born.

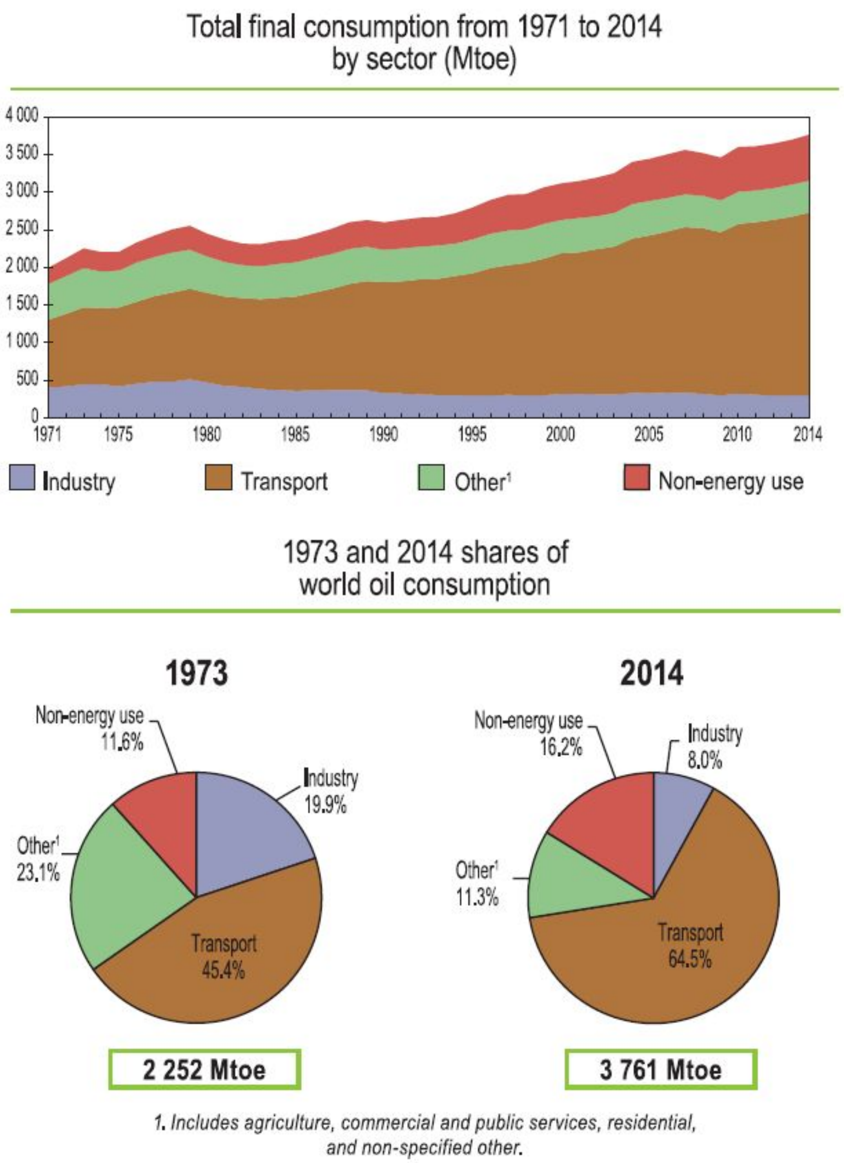

Figure 1. Total final consumption of oil worldwide 1971-2014 (IEA, 2016)

Though the transportation technologies in use by people around the world today are as diverse as what nature has created through evolution, there is one undisputable tyrant when it comes to fueling our vehicles - oil. Gasoline for automobiles, diesel for heavy duty vehicles and ships, and kerosene for jets are all produced through the refining of a single barrel of crude oil. These petroleum products power 93% of the transport in the world, meaning transportation is the sector most monopolized by fossil fuels (IEA, 2017c). Inversely, as shown in Figure 1, the transport sector accounted for almost two-thirds of the world's end-use oil consumption in 2014 (IEA, 2016). This dissertation will focus specifically on personal road transportation, which is comprised of over 1 billion vehicles worldwide[1] and represents the largest segment of the transportation sector (IEA, 2017b). The most intriguing aspects of Figure 1 are that the global reliance on oil has actually increased by 67% since the first oil shock of 1973, and that the transportation sector is almost entirely responsible for this fact while other sectors have begun to diversify away from this energy source with proven price and supply instability (IEA, 2016).

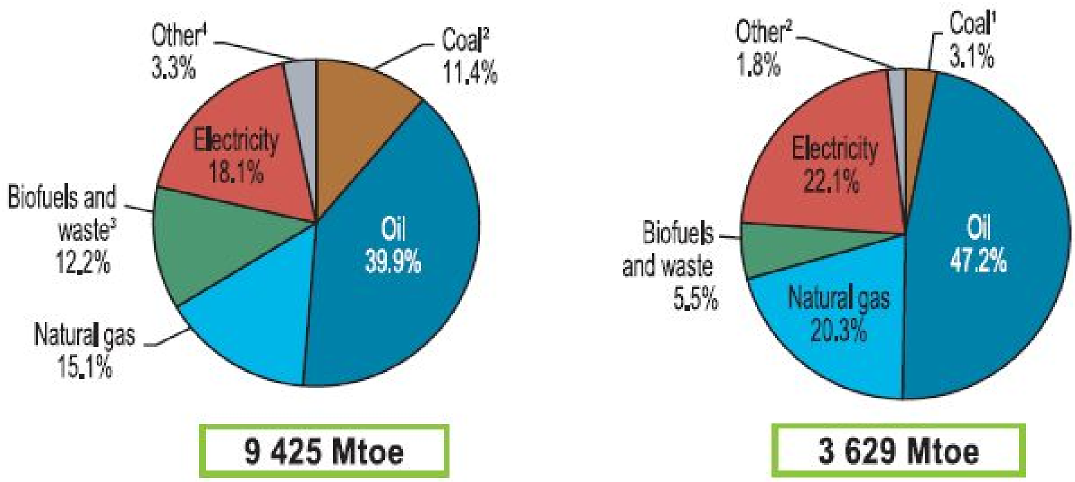

Figure 2. Total final consumption by fuel in 2014 worldwide (left) and by OECD countries (right) (IEA, 2016)

Moreover, Figure 2 shows that developed countries[2] use a disproportionate amount of oil compared to the rest of the world despite their financial and technical capacity to diversify their energy resources. Figure 3 depicts how the energy consumption levels in the OECD have slightly increased and remain the largest share of global demand despite their manifold rational motivations to curb it. This dissertation will focus exclusively on the United States and the European Union, the two historical world leaders in cumulative oil consumption, international affairs and technological innovation in modern transportation. While there are other major actors in the global economy of great interest to this topic - case studies of China, Brazil, India,

[1] An all-time high of 1.1 billion in 2015 was the most recent statistics recorded by the International Energy Agency (IEA)

[2] By the definition of the Organisation for Economic Co-operation and Development (OECD)

Australia and Japan would be extremely worthwhile - the US and the EU still maintain somewhat of a *de facto* leadership status in today's sociopolitical and economic spheres. The obvious macro-level similarities between the two regions - capitalist democracies with Western value systems - and the manifold meso- and micro-level differences provide fertile ground for intricate analyses into the true nature of our oil dependency and how to break it. The historical evolution of transport is obvious to these populations, so why has the transition away from our current fuel source made such little progress compared to other energy-intensive sectors?

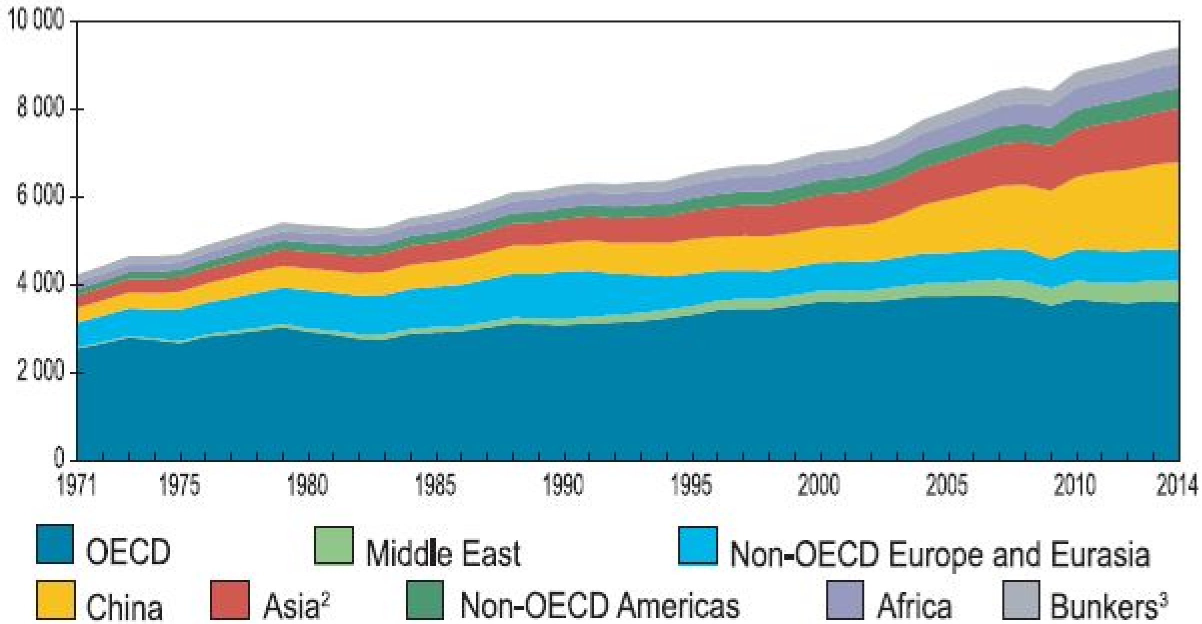

Figure 3. Total final energy consumption by region from 1971 to 2014 (IEA, 2016)

The short answer to this question is that transportation fuels have been exemplary of the institutional theories of path dependence and the "lock-in" effect, to be explained in greater detail in Chapter 2. The transition away from the ubiquitous use of fossil fuels for our land, rail, air, and marine travel will constitute nothing short of a revolution. The impetus for spurring the transition at this particular moment in time derive from the environmental impacts attributable to the combustion of these hydrocarbon fuels. Particulate pollution, ozone depletion, acid rain, heavy metal emissions and, most relevantly to this discussion, atmospheric carbon release contribute to the deterioration of air quality, loss of biodiversity, acidification and rising of oceans, degradation of soil quality, severe warming of global temperatures and a general change in the Earth's climate system which in time may render the planet unfit for recognizable human civilization. Ironically, if we do not break the lock-in of our dominant fuel sources, we may in fact facilitate mother nature in breaking the lock-in of her dominant species.

However, our knowledge of these environmental effects has only been scientifically established relatively recently in comparison with the adoption of petroleum for transport. In the time that it took science to catch up with our actions, we had already developed a systemic addiction to oil-based transport. Figures 4 and 5 illustrate how transportation has stood apart from other economic sectors in the US and the EU, respectively, in terms of decarbonization, having actually become *more* carbon intensive than it was in 1990 while almost every other sector has cut emissions (EPA, 2017; Vis, 2016). Figure 6, meanwhile, depicts the required global GHG emissions trajectories based on the remaining carbon budget to limit temperature rise by 2100 to 2℃ or below as calculated by the International Panel on Climate Change (IPCC) in 2014 (IPCC, 2015). Figure 7 illustrates the "emissions gap" we are destined for compared to those targets by following our current policies and activities Unfortunately, the new 'invisible' threat of climate change is no match against the lock-in of oil observed today, an interdependent system of institutional, technical, political, economic, social and cultural arrangements which have evolved together for over a century (Seto et al., 2016; Unruh, 2000)

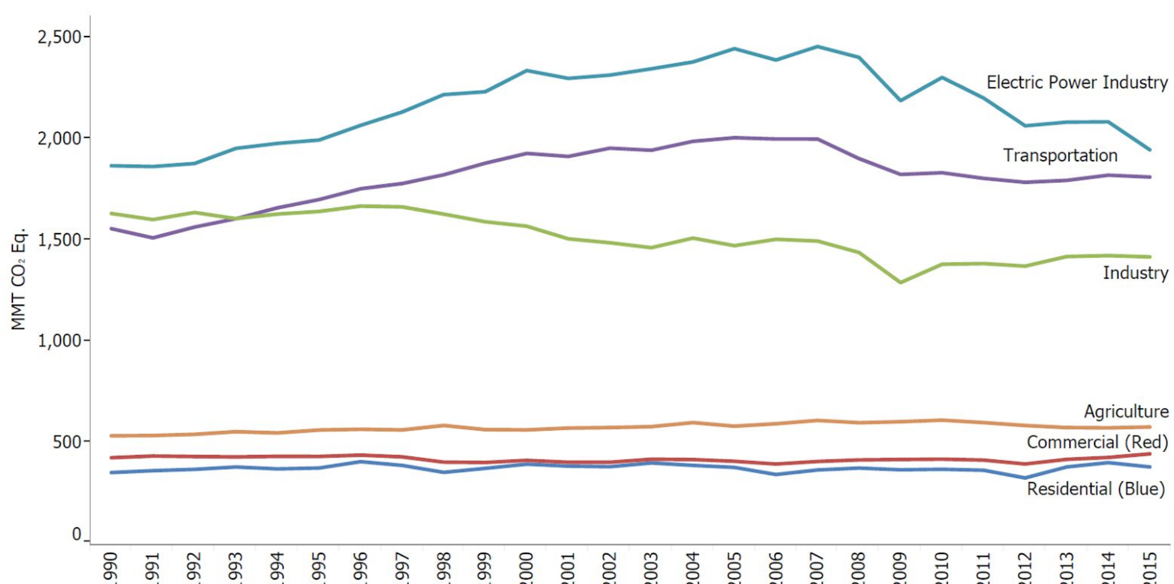

Figure 4. GHG emissions by sector in the US from 1990 to 2015, in which transport has shown the largest relative increase (EPA, 2017)

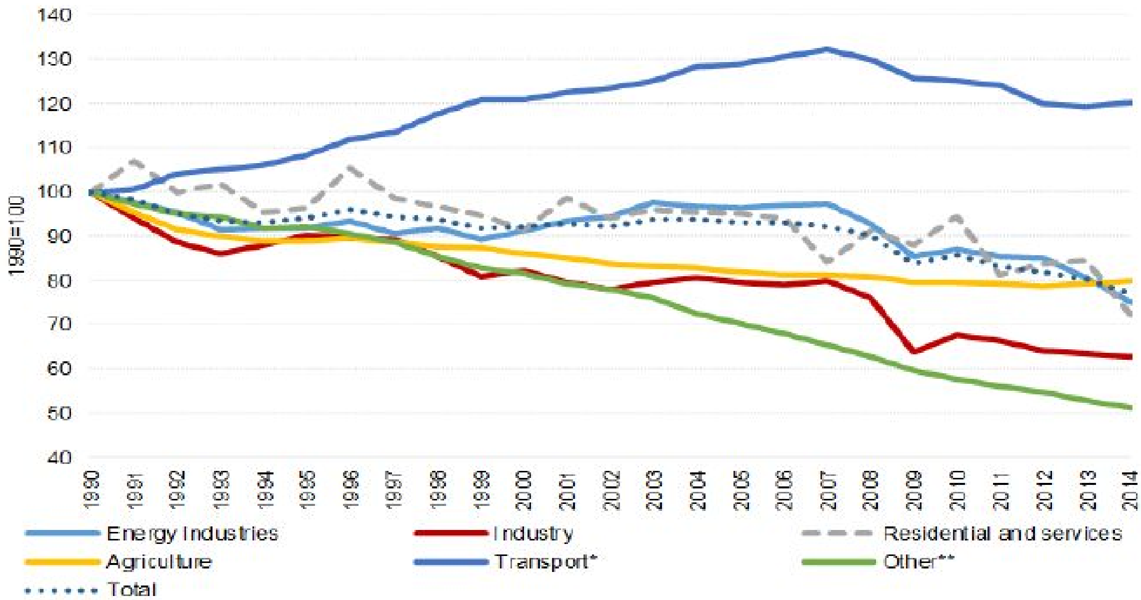

Figure 5. GHG emissions by sector in the EU as a percentage of 1990 emissions, showing transportation to have an opposite trend to the decarbonization in the rest of the economy (Vis, 2016)

On the surface, the issue at hand is of course a technological transition, but to label it as such propagates the misleading idea that we are simply waiting for a superior replacement to petroleum which has yet to arise. While the role of innovation should not be understated, we have never lacked for alternative fuel systems. Electricity and biofuel (ethanol) were both used to power automobiles before gasoline-burning engines were popularized, and today they again represent the leading prospective competitors to oil-driven transport. Electric vehicles (EVs) and a number of biofuels are road-ready technologies with certain drawbacks but at least as many proven advantages compared to petroleum, but they haven't been able to establish anything close to a commensurate market share. The following chapters will expound upon the environmental urgency for a movement toward decarbonized transportation and assert that market forces in the status quo political economy will never foster the transition. The role of government, private actors and civil society will be explored to examine reasons for past failures and their implications for the approach to foster a sustainable future of personal transportation.

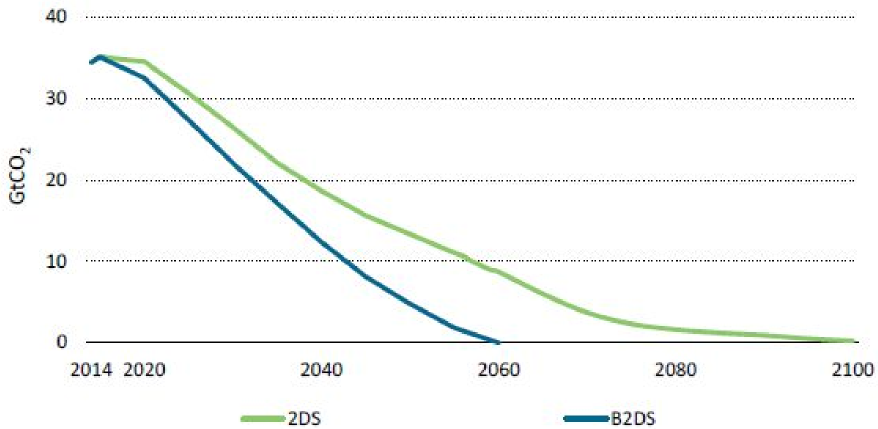

Figure 6. Required GHG emission trajectories to meet COP21's 'Two Degree Scenario' (2DS) and its 'Beyond Two Degree Scenario' (B2DS) for limiting global temperature rise by 2100 (IEA, 2017b)

Elements of neo-institutional theory, particularly path dependency and the lock-in effect, are very befitting to the development of transportation systems, and they form the basis of the theoretical framework to be presented and defended in Chapter two. The works of Douglass North, Paul David, and Gregory Unruh were of particular significance to the formulation of the framework. The chapter will go on to explore the early history of automotive transport while applying the theoretical concepts in parallel. Chapter three shall develop the theoretical context further, introducing the newly derived concepts of *inherent lock-out* and *intentional lock-out*, while continuing to provide historical perspective on how the personal transport system evolved to become so oil-dependent. Chapter four will compare the institutions surrounding transportation between the US and the EU and how they have shaped vehicular activity today. This chapter shall include an overview of their transportation decarbonization policies throughout the years and the implications for the future. Chapter five will conclude the dissertation with an analysis of how path dependency may connect the present to the future, and how we can use concepts from this theoretical framework to break the lock-in of oil in transport while preventing the lock-in and lock-out of new technologies in the road ahead. Policy implications of the findings will also be compiled in the end for both regions.

There will be a sequence of overarching questions that this dissertation seeks to address throughout these chapters. First, what are the major barriers to the decarbonization of transport in the EU and the US, and what are the exploitable motivations? Second, what insights can be gained from a path dependency perspective of automotive history for policy making and to what extent have they been acknowledged by either government? Third, what would a sustainable transportation sector look like ideally in either region and how should they each shape their short-term, medium-term and long-term visions?

Both deductive and inductive reasoning will be applied throughout, and although some quantitative methods shall be incorporated into the analyses, the answers sought are qualitative. By nature, this implies that they are open to a certain degree of subjectivity and should not be regarded as absolute truths. It shall be the responsibility of the reader to maintain an objective eye in assessing the arguments and logic presented throughout the text. The author, meanwhile, shall disclose his hypotheses below with the intention of appraising their veracity and not of selectively citing evidence in their favor.

First, it is the author's expectation to find that the US is hampered above all else by a political and cultural self-identity in oil dependency, and that alternative fuels have been developed thus far not as competition but as a supplemental supply for energy security and techno-economic reasons, both very strong political arguments for the future. The EU, in contrast, is politically and socially motivated to transition away from petroleum for both environmental and energy security reasons, but its progress has been stunted due to technological inertia and a lack of coordination in political efforts. The author's preconceptions of the second question are that the EU has acknowledged the issue of carbon lock-in but has struggled to implement cross-sectoral policy approaches due in part to the segmentation of the European Commission, while US lawmakers have refused to adopt this institutional view and even actively denounce it. A comparison between the policies and outcomes between the two should indicate that incorporation of the institutional model can produce results faster than the pure market economy ideology. The third question will require technical and quantitative research to answer, so the hypothesis can only indicate a surface-level understanding. The short term objective in the EU should be to displace fossil fuels as quickly as possible through support for enhanced market penetration of competitors, while in the US the focus should be on further development of technologies to reduce costs and improve market readiness as the current political climate is not conducive to the movement. Medium-term objectives in both regions should turn to developing infrastructure to support the incoming technologies and to provide technology-neutral support for all alternative fuels. The long-term vision might differ subtly between the two, but it should consist of a liberalized market of sustainable transportation fuels including ethanol, biodiesel and EVs, among others, and a vehicle fleet capable of using them interchangeably.

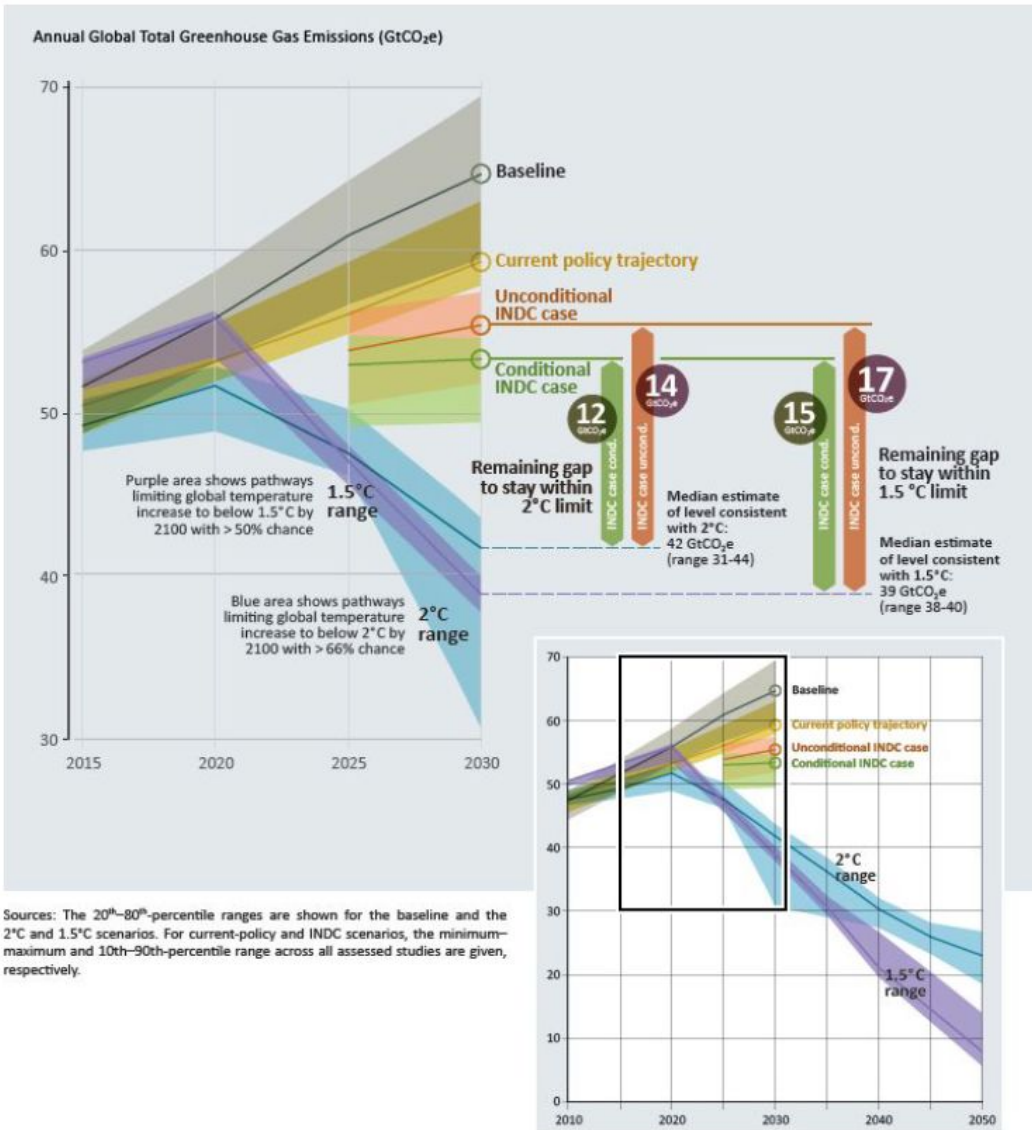

Figure 7. Greenhouse gas emissions trajectories for various possible scenarios given current economic practices and policy proposals, and the calculated "emissions gap" that still remains to be addressed in order to keep temperatures below the targets accepted at COP21 in 2015 (UNEP, 2016)

Chapter 2. The Path Dependent Rise of Modern Transport

2.1 Increasing Returns Economics and the Lock-in Effect

Path dependence is a concept that has become well established throughout the social sciences over the past three decades which postulates that the future is molded by the past or, more simply put, that history matters. The idea is a derivation of chaos theory and "the butterfly effect" from the mathematical realm, which can provide a more precise characterization of the phenomenon (David, 2001; Liebowitz & Margolis, 1995). Stochastic, insignificant events can alter the course of a dynamic system, causing far-reaching and long-lasting impacts which might never be traced back to the original event. The lock-in effect describes a special case of path dependence in which those initial conditions determine a rigid trajectory insensitive to subsequent agents of change, regardless of how beneficial they may be. Path dependence and lock-in are perhaps most widely understood in the context of technological development, as scholars have explored popular examples such as the QWERTY keyboard, alternating current, VHS and DVD video formats and notably enough, the internal combustion engine (Arthur, 1989; David, 1985, 2001; Pierson, 2000; Unruh, 2000). Also of significance to this dissertation are its previously described effects on policy, macroeconomics, individual behavior and societal institutions.[3]

The special conditions in which path dependence can lead to technological lock-in are described by the often-overlooked economic principles of increasing returns and positive feedback in the early phases of technological adoption. When multiple technologies are competing for public acceptance in a new economic space, the ultimate determinant of success is prevalence. When new goods are introduced to consumers, familiarity breeds trust, and trust drives demand. One particular technology may gain an early advantage over the competition due to any number of factors which act as optimizing agents (Unruh, 2000). These can include timing, whether it's the first out of the gate or it arises at the perfect juncture of societal need; deployment and marketing strategy; historical circumstances; or random contextual events that

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[3] To ensure reader comprehension, "institutions" will be defined here as "the humanly devised constraints that structure political, economic and social interaction. They consist of both informal constraints (sanctions, taboos, customs, traditions, and codes of conduct), and formal rules (constitutions, laws, property rights)," (North, 1991).

may appear insignificant (Arthur, 1989; Unruh, 2000; Pierson, 2000). Especially in knowledge-intensive and highly networked sectors, any subset of these optimizing agents can lead to the selection of a singular dominant design regardless of whether it is technically superior or economically optimal.

This design may also benefit from increasing returns through four different mechanisms, some of which may be in place before its emergence as the dominant design but which all propel its growth thereafter. The first of these mechanisms is increasing returns to *scale*, which allows the industry to overcome fixed or startup costs. The second is *learning effects*, which describes the industry's ability to develop expertise and adapt to consumer preference. Third, increasing returns by *network effects* is a broad concept which means that the product's value to its users increases as its level of pervasiveness increases in society. Finally, *adaptive expectations* can drive increasing returns as consumers and producers adapt behaviors to their new expectation that this dominance will persist (Arthur, 1994). The market in effect propagates a self-fulfilling prophecy through these positive feedback mechanisms until the cost of switching to a potentially better design becomes too high. When this point is reached, the technology therefore becomes locked in.

Figure 8 provides a simple qualitative model of the developmental path of a given technology as it gains acceptance by the market, relating the phenomenon of increasing returns to the law of decreasing returns which has dominated mainstream economic discourse in the modern era (Pierson, 2000; Unruh, 2000). Mainstream economics is driven by neoclassical theory (Colander, 2000), which professes that a deregulated market in which private actors are driven by rational self-maximizing behavior will result in a unique equilibrium point representing the optimally efficient allocation of resources in every established market. The assumption that economic actions follow the law of diminishing returns lends predictability to the futures of markets through mathematical models. However, conventional economic thought is typically unconcerned with how these markets came to be established. Economic theorists have formed several schools of thought which address the topic: new institutional economics (Coase, 1998), evolutionary economics (Arthur, 1994) and historical economics (David, 2000), among others. They unite over the dynamism of economic systems, the existence of multiple potential equilibria, and the role of influences external to the market (history and institutions in particular) in determining the ultimate equilibrium point. The author will not follow one particular theory dogmatically, but will collectively refer to their common principles as “increasing returns economics” (Arthur, 1994) and rely upon them to explore how the oil industry secured a monopoly on transport fuels and how we can foster a new market for sustainable transportation technology.

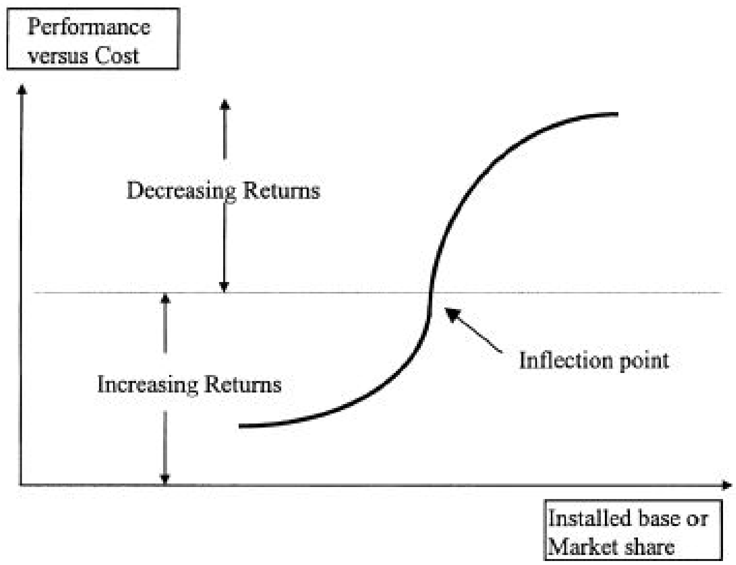


Figure 8. Simplified model of the performance-to-cost ratio as a function of the level of adoption. Once a technology achieves a critical mass in the early stages of evolution, various forces can generate massively increasing returns on subsequent investments (Unruh, 2000)

Before embarking down this path, it is important to note that there exists considerable dissent as to the relevance of path dependence from mainstream economists who maintain that a liberalized market is invariably capable of returning an efficient equilibrium. One frequently cited rebuke of the lock-in effect breaks path dependence into three sub-categories: first-degree, second-degree and third-degree (Liebowitz and Margolis, 1995). Each category in fact describes dynamic processes which are hypersensitive to initial actions and resistant to change, but they argue that the outcomes of this path dependent behavior must be qualified. They use first degree to indicate when the resulting path is no less optimal than any of the feasible alternatives, and thus there is “no implied inefficiency” (ibid.). They define second-degree path dependence as a case when information concerning options at the starting point is not fully available, so the choice of a suboptimal path was not knowable and thus not “inefficient in any meaningful sense” (ibid.). Finally, third degree path dependence can be declared when an inefficient outcome is dictated by initial conditions but there exists or existed a feasible superior alternative. Otherwise known as "remediable" path dependence, to the critics this represents the only scenario in which path dependence is of any concern. However, by their own declaration, "the evidence is that there are as yet no proven examples of third degree path dependence in markets" (Liebowitz and Margolis, 1998).

While their logic for categorizing the concept introduces valuable insights into the debate over a consensus interpretation of path dependence, their critiques of its relevance are frankly irrelevant to the topic of this thesis. Their appraisal of the subject is grounded in the defense of their economic ideology, as they admit in their own words: "third-degree path dependence is the only form of path dependence that conflicts with the neoclassical model of relentlessly rational behavior leading to efficient and therefore predictable outcomes" (Liebowitz and Margolis, 1995). It has been subsequently (Pierson, 2000) pointed out that this one-dimensional perspective conveniently dismisses some of the central tenets of the lock-in effect along with some realities of the economy. Their argument that remediable path dependence is inherently prevented by market mechanisms because well-informed private actors will sacrifice short-term maximization for long-term interests is only relevant at the individual or firm level (and not a true generalization, as will be seen below). However, "many of the benefits of increasing returns are external to individual firms and cannot be fully captured by individual investors and entrepreneurs" (Pierson, 2000). Moreover, they ignore the institutional context in which their counterparts have framed the lock-in effect, and that the formation of institutions themselves are subject to path dependence (North, 1991).

In fact, increasing returns economics is not a rejection of the mainstream economics but rather a progression building upon the same market-based foundations. Economic theories, like technologies, institutions, policies and human society in general, are dynamic systems which evolve through experience and innovation. Seeing as they are complex, knowledge-intensive systems, these theories are highly sensitive to the increasing returns mechanisms described earlier in this chapter as they enter the public eye. Indeed, a historical evaluation of the field of economic analysis shows that it has itself been prone to the lock-in effect, which provides ample explanation for the observed resistance to accepting increasing returns into the discipline (David, 2001).

2.2 Carbon Lock-in and the Transportation Techno-Institutional Complex

Oil-based transportation is so deeply ingrained in developed society that it has become a mere fact of life. It represents the most direct point of contact to fossil fuels for the hundreds of millions of car owners in the EU and US (Dadush and Ali, 2012). While electricity, heating and cooking are also daily needs which rely on fossil fuels, we are not exposed to the coal burning at power plants, and the majority of people in modern communities are not responsible for filling their natural gas or oil tanks at home like they are their gasoline tanks. This can breed a sort of emotional connection between people and petroleum; they have relied upon the product their whole lives, they trust it in terms of quality and performance, they know how easy it is to obtain, they trust (counterfactually) in its constant supply, they know which octane rating suits their vehicles, they know approximately what it will cost at any given time, and they don't know what they would do without it. Gasoline consumption has become synonymous with driving, and driving has become a symbol of independence, control, and status. Car ownership allows people to choose where to live despite where they work, it frees them to shop where they want, it means their schedules are not at the mercy of bus and train routes, it liberates teenagers from their parents (and frees parents from the chore of chauffeuring), and in some circles it can even be a reflection of their self-worth. A telling indication of the importance of car ownership to developed societies comes from a 2012 study seeking to quantify the middle class in developing countries (Dadush and Ali, 2012). The metric chosen for their assessment? Car ownership per capita.

The term for this phenomenon within path dependence theory is the behavioral lock-in of cars in society, which has been presented in increasing returns economics studies as the final phase of technological lock-in (Seto et al., 2016; Unruh, 2000). According to analysts, affecting change in the behavioral patterns and personal preferences of society may prove to the longest and most complex challenge of them all (Kohler, 2012). The discussion will arise in Chapter Four as to what extent this barrier needs to be tackled, but the simple fact that it exists illustrates how pervasive the lock-in of petroleum-powered automobiles has become. Once a dominant design has been selected and is on an increasing returns trajectory, the lock-in progresses stepwise through investments in supporting infrastructure, the co-development of complementary technologies, the coevolution of private and societal institutions, and finally the penetration of the individual psyche to develop a dependence on the technology. These events are causally linked, but over time they also develop an interdependence. Together, they have been deemed the *techno-institutional complex (TIC)* resulting from a large-scale techno-institutional lock-in (Unruh, 2000). In the context of our economy's systemic addiction to fossil fuels consumption, the analogous term is *carbon lock-in* (ibid.).

Theoretical framework aside, carbon lock-in is a self-explanatory expression and an undeniable reality. Over 80% of the world's energy consumption - 81.1% in 2014 to be exact, as displayed in Figure 9 - comes from oil, natural gas or coal (IEA, 2016). In 1973, the year of the Yom Kippur War and the resultant oil embargo placed upon the US by the Organization of Petroleum Exporting Countries (OPEC), that figure was 86.7% (ibid.). Despite this materialization of the concerns over a cartel-dominated industry, a second oil shock just six years later, the advent of new technology such as nuclear and renewables, the knowledge of its finite nature and now the existential threat of climate change, the fossil fuels industry has actually increased production by 2.1 times and lost only 5.6% of the world energy market over the past 41 years (ibid.) The fossil fuels sector is characterized by "the largest network of infrastructure ever built, reflecting tens of trillions of dollars of assets and two centuries of technological evolution, and is supported by an equally extensive complex of co-evolved institutions, policies, and consumer preferences" (Seto et al., 2016). The persistent use of petroleum in transportation despite the existence of alternatives and compelling motivations for switching is a subdivision of carbon lock-in, and the network of actors and mechanisms comprising it will be henceforth referred to as the *transportation techno-institutional complex (TTIC)*. The analysis below of the very beginnings of motorized personal transport reveals how significant a role path dependence played in the formation of this complex. This historical perspective seeks to provide insight into the nature of the personal transportation sector and into policy implications for a sustainable future of personal transport.

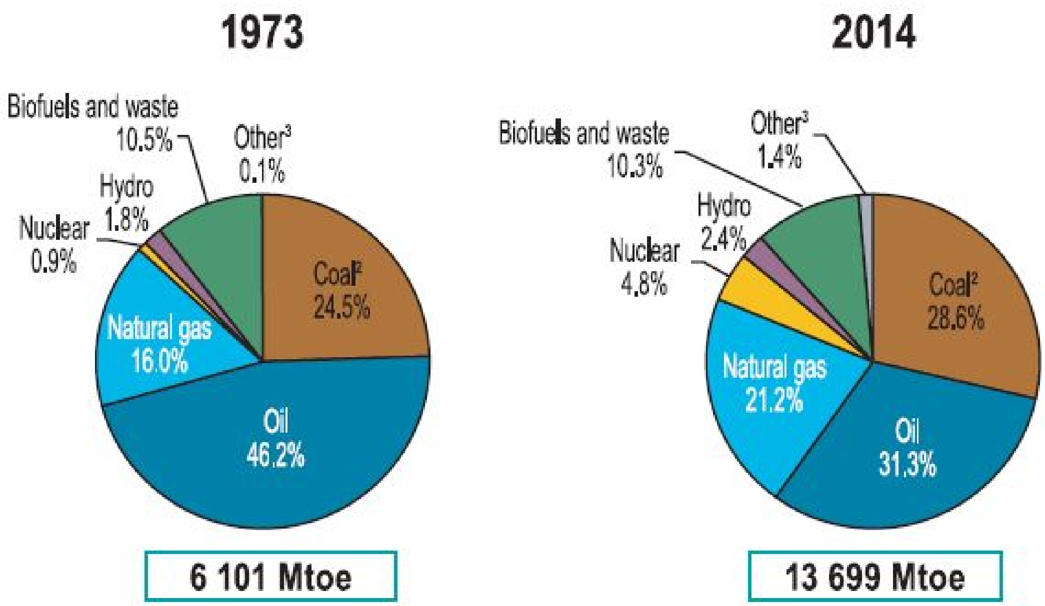


Figure 9. Total worldwide primary energy supply by fuel, comparing 1973 to 2014 (IEA, 2016)

Near the turn of the 20th century, the steam engine, the electric motor and the internal combustion engine (ICE) all promised to replace the horse-drawn carriage and forever change personal transport. In 1885, the ICE was actually considered the least viable option as it was dangerously explosive, noisy, polluting, difficult to operate, and a complicated new design (Arthur, 1989; Matulka, 2014; Unruh, 2000). The EV, by contrast, was emissions-free, quiet and easy to drive, and the steam engine was already a familiar, tried and true technology to the public from its use in trains and boats (Matulka, 2014). All three were commercially available in the US by the turn of the century, at which point steam vehicles represented 40% of cars on the road, electric carriages 38%, and ICE automobiles just 22% (Chan, 2013). During this era of ferment, technical capabilities, aesthetics, practicality and price were all heavily scrutinized, and EVs began to pull ahead in both the US and Europe.

While EVs suffered from the “range anxiety” issue widely publicized in today’s media, limited range was in fact an issue for all three competitors in a world where petrol stations were not an established institution. In fact, French car manufacturer BGS built an EV in 1900 which set the world record for the longest range of any automobile at the time, at 290 km on a single charge (Chan, 2013). An EV was also the first vehicle to break the 100 km/h speed barrier, a Belgian race car in 1899 (ibid.). The EV was also very practical for the time, when personal transport was typically envisioned within the confines of cities as roads outside of cities were poor or non-existent (Chan, 2013; Matulka, 2014). They were very well suited for urban areas where electricity grid was well developed and where air and noise pollution from the competitors was a nuisance (ibid.). Cars were only afforded by the wealthy in those days, and EVs were first to occupy the "luxury" market with moving status symbols costing $3,000 (around $84,000 today) on average (Chan, 2013). Indeed, advertisements such as the one in Figure 10 combined with its quiet, clean, easy-to-operate features built a social stigma of the EV as a "woman's car" (ibid.). However, there were also basic EVs offered under $1,000 (around $24,000 today), similarly priced to the competing technologies (Chan, 2013).

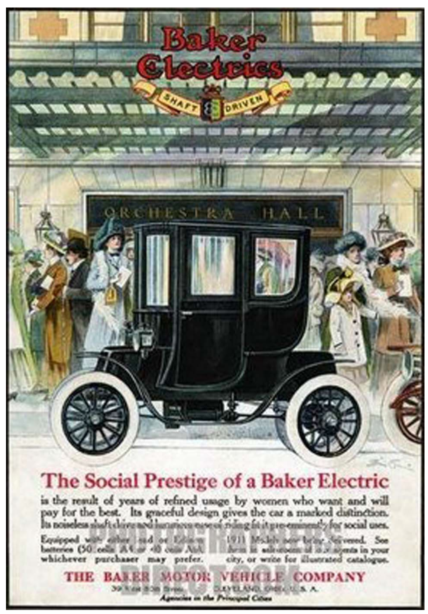


Figure 10. US advertising poster for a Baker electric vehicle, circa 1900 (Chan, 2013)

This would suddenly change in 1908 when Henry Ford had the genius and courage to pioneer mass production of the Model T. Ford understood importance of scale economies and that this one-time investment risk could allow him to undercut the competition in price and capture increasing returns to scale. In 1912, the average gasoline car cost $650 while EVs were going for an average of $1750 (Chan, 2013). His foresight also gave him confidence that simply producing more cars would generate increasing returns by network effects as more Model T's on the road meant more market exposure. Further network effects also arose in the form of positive externalities for the industries of intermediate goods such as rubber, steel and glass. His unique production method required these industries to develop design-specific supply relationships with him, which they were obliged to do as he provided them with a new, sustained revenue stream (Unruh, 2000). This network economy was then able to propagate itself, as the ICE producers could follow this production model using the supply chain already established.

Now that a larger segment of the population had access to automobiles, there was a growing demand for new infrastructure. In terms of range, steam vehicles traditionally held the lead as they could easily refill on water from horse troughs, but in a stroke of bitter irony troughs were now disappearing as horses were being replaced (Unruh, 2000). General Electric began constructing EV charging stations in the US, but they were impractically slow and could not be installed everywhere at that stage of electricity grid development (Chan, 2013). Electricity was also very expensive at the time, costing up to four times as much as gasoline per unit energy (ibid.). The ICE, on the other hand, stumbled upon yet another network externality as its rise provided a market opportunity for the booming oil industry. “By 1920, gas stations made their way across the United States and filling up a car with gas became very easy” (Chan, 2013).

Long distance roads thus became a marked advantage for the ICE, and also by 1920 a major government road and highway expansion program was underway. This has been attributed in no small part to a joint lobbying effort by the ICE auto industry, its aforementioned business partners and others such as the cement industry (Unruh, 2000). They were so successful that this coalition has remained united to this day as the highly influential “US highway lobby,” the political embodiment of the TTIC. This amalgamation of historical circumstance, timing, entrepreneurial spirit from Ford and subsequent network effects thus led to the selection of the ICE as the dominant design in personal transportation. Infrastructure, coevolving industries and societal institutions were already converging around the ICE in a positive feedback loop diagrammed in Figure 11, and after an iterative process this TTIC becomes locked in as its societal value grows to the point of dependency.

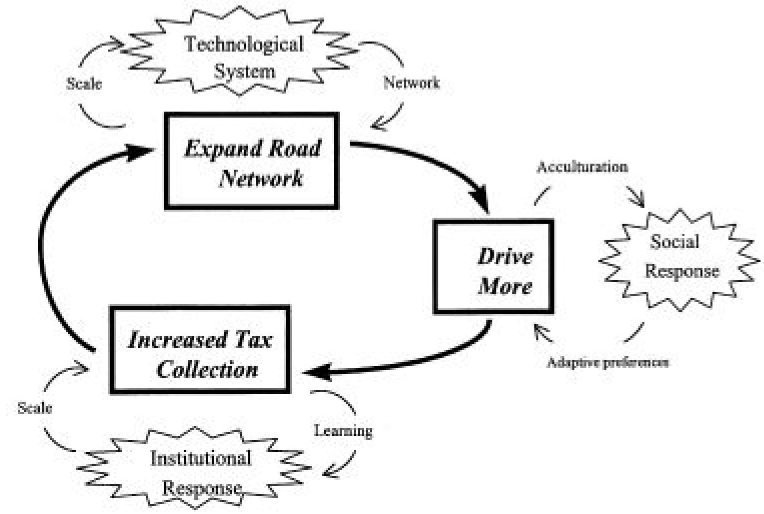


Figure 11. A rudimentary illustration of the mechanisms driving the lock-in of the transportation techno-institutional complex. The starting point lies somewhere within the "technological system" and "expand road network" sub-loop (Unruh, 2000)

What is not evident from this 'battle of the engines' is how petroleum monopolized transportation fuels and came to be the central cog of the TTIC. In fact, the first ICE prototype ever developed by American Samuel Morey in 1826 used ethanol as its fuel source, as did the first engine designed in 1859 by the more well-known German inventor Nikolaus August Otto, namesake of the Otto-cycle engine which would run on either gasoline or alcohol (Carolan, 2009; Bill Kovarik, 1998). Ethanol was a popular and cheap fuel for lamps in those days, burned at a rate of over 13 million gallons per year (Carolan, 2009). It was prevalent in cooking stoves and industry as well, totaling an estimated 90 million gallons per year (Kovarik, 1998). But that would quickly change due to completely irrelevant external events. The US broke out in civil war in 1861, and the Union was forced to introduce new taxes through the Internal Revenue Act of 1862 to help fund the military. This package included a $2.08 per gallon tax on alcohol which was intended only for recreational beverages but it failed to specifically exempt fuel ethanol (Kovarik, 1998; Carolan, 2009). It is pure serendipity that oil was struck just three years earlier *and* that it was the light variety of crude oil, refined to produce 75% kerosene, allowing it to become a cheap alternative (Carolan, 2009). This was a shock to the ethanol industry, and many distilleries would not survive as other industries were forced to rapidly adopt petroleum to remain competitive. And thus, an overlooked historical detail allowed the oil tycoons to capture increasing returns by network effects with the lighting sector, adaptive expectations and economy of scale in one fell swoop as oil demand skyrocketed to 200 million gallons per year within a decade of discovery (Kovarik, 1998).

While the excise tax on alcohol was busy dissolving the US ethanol industry, the opposite trend was observable in Europe. As there were no major oil fields discovered on the continent, European powers were not content to rely on imported American petroleum for their energy needs. Germany, France, England and the Netherlands among other nations looked to secure energy independence by passing measures which exempted industrial ethanol from taxation (Carolan, 2009). Germany went even further to ensure constant price equivalence between alcohol and petroleum by applying a market-adjusted simultaneous subsidy for alcohol producers and tariff on petroleum imports (Kovarik, 1998). By the turn of the century, German alcohol production exceeded 112 million gallons, primarily from small farm distilleries constructed by a government program (Carolan, 2009). The French government also provided public support to ethanol through the Ministry of Agriculture, producing 8.3 million gallons in 1905 (Kovarik, 1998). The European ethanol industry was in fact beginning to generate network effects, as everything from automobiles, farm equipment and trains, to household appliances such as heaters, laundry irons and even hair curlers had alcohol-powered versions in the market (ibid.).

In 1908, Teddy Roosevelt signed into law the Free Alcohol Bill to repeal the tax on fuel ethanol with overwhelming support from Congress, farmers, the media, and even automobile manufacturers (Kovarik, 1998). The Model T, released that same year, was actually fully capable of running on either gasoline or ethanol. Henry Ford, having grown up on a farm, was actually a public proponent of alcohol fuel over gasoline. In 1925 he was quoted in the New York times as saying, “The fuel of the future is going to come from fruit like that sumach out by the road, or from apples, weeds, sawdust — almost anything. There is fuel in every bit of vegetable matter that can be fermented. There’s enough alcohol in one year’s yield of an acre of potatoes to drive the machinery necessary to cultivate the fields for a hundred years” (ibid.). Right alongside him was Charles Kettering, the head of research at rival GM, who cited both energy security reasons - the finite nature of petroleum as well as the reliance on foreign supplies - and engineering reasons - the “knocking” effect characteristic of gasoline but not ethanol, the cleanliness of ethanol exhaust and the higher octane content of alcohol (ibid.). Moreover, Detroit Board of

Commerce Representative James S. Capen testified during the Free Alcohol Bill Senate hearings "that alcohol was 'preferable' to gasoline because it was safer, 'absolutely clean and sanitary,' and because 'artificial shortages' could not raise the price in the future. The biggest problem for auto makers, Capen said, was not so much cost as the question of long term supply" (ibid.). Therein lies the rational thought that appears to escape carmakers today: the auto industry does not depend on the petroleum industry, but rather vice versa, and it is in automobile firms' best interests to survive in a post-oil economy.

However, gasoline in the early 1900's was incredibly cheap and in constant surplus as a toxic waste product of kerosene production (Kovarik, 1998; Unruh, 2000; Carolan, 2009). At the same time, new oil fields were being discovered and developed in Texas, driving the price down to just $0.15 per gallon (Kovarik, 1998; Carolan, 2009). Still, fuel ethanol may have remained competitive[4] if not for the US requirement for it to be denatured, or rendered undrinkable, to avoid the persistent 'sin tax' held in place largely due to the Temperance Movement (Carolan, 2009). This was predominantly accomplished by blending in methanol, a much more costly alcohol, driving ethanol prices to approximately $0.30 to $0.35 per gallon (ibid.). As ethanol was not able to compete in price under initial market conditions, the industry never reached critical mass for attaining a scale economy in the US. In contrast, Standard Oil had consolidated 90% of all domestically refined oil (Carolan, 2009), affording it the luxury of capturing increasing returns to scale in one market (e.g. kerosene lamps) and reinvesting them to develop another market (e.g. gasoline filling stations). This monopolization allowed the firm to rapidly improve its methods, develop logistics networks, and even to control prices, as declared in the antitrust Supreme Court victory against Standard Oil in 1911. By then, however, the rapid discovery of new oil reserves had already led to many more highly profitable refining companies. Thus, by a separate set of historical circumstances, fortuitous timing and business strategy, petroleum emerged as the dominant fuel source in direct parallel with the rise of the ICE. They have since evolved side by side to form the core of the TTIC we know today.

An important analogous example to the TTIC is that of the telephone. The advent of telephony also set off a positive feedback loop which benefitted greatly from increasing returns by network effects - phones became more useful and attractive as more people adopted them. As

[4] Ethanol prices in Germany were reported to be $0.13 per gallon at the time.

society adapted to the technology, it was soon expected of everyone to buy in. Eventually the government intervened to ensure that this would be possible, enacting a social welfare program to extend telephone cables to rural and poor communities. It has been claimed that an unmistakable sign of a TIC lock-in is when governments use formal justification for using policy to override market forces (Unruh, 2000). Four commonly cited rationale are ‘universal service,’ as in the case of telephone networks; ‘natural monopoly,’ which the US government claimed to regulate phone network operators; ‘national security,’ which in fact was the justification for a $30 billion public investment into the automobile industry during World War II; and ‘public safety,’ which was used to introduce driver licensing, thus setting up a new formal institution around of the TTIC (ibid.). The other important lesson to be learned from the telecommunications TIC is that techno-institutional lock-in is by no means a permanent condition. The ubiquitous landline has since been replaced by a new dominant design, the cellular phone and its co-developed network of cellular towers. The transition was not immediate, but it grew much more rapidly as the technology matured and networks began to expand. In other words, the technology began to capture increasing returns from learning effects and network effects and fed off a positive feedback loop until a once-basic necessity was rendered obsolete.

Indeed, human ingenuity and the constant advancement of science dictate that technological shifts are inevitable. The lock-in of a TIC only presents barriers to the diffusion of new options, thus delaying the arrival of a new dominant design. Even if the originally selected and locked-in dominant design within a TIC is objectively proven to be techno-economically superior to all of its competitors at the time of adoption, “incremental change in challenging technologies is always diminishing a dominant design's technological advantage” (Unruh, 2000). The following chapter shall continue to explore the history of carbon lock-in within personal transport and how it has been able to barricade itself from change for so long. The question shall also be raised of whether the ICE-petroleum combination truly was the technically and economically superior choice at the time.

Chapter 3. Locking in Lock-out

3.1 Preface

The evidence of path dependency in the genesis of today's monolithic transportation complex is hard to ignore whether the reader accepts it as a consequential phenomenon or not. Up to this point, the analysis has mostly maintained a high-level perspective, in which each industry or technological alternative is a functional unit within society. The purpose of each of these units is to gain a relative advantage to the others and win favor in the market, but as explored above this competition is influenced by countless unpredictable, exogenous factors out of their control. Following the lock-in of a dominant design, the industry remains a dynamic system but no longer exhibits the sensitivity to external circumstances characteristic of the era of ferment. The author proposes that there are two major categories for the mechanisms that ensure the lock-out of competing technologies as the TIC grows in influence. The first is a set of economic and institutional circumstances which naturally oppose a diversified market, dubbed *inherent lock-out*. This implies that certain aspects of technological lock-out are caused by instinctive, rational behavior from actors within the TIC and surrounding it. It is important to note, however, that 'inherent' in this context is not to say 'inevitable'; lock-in and lock-out may materialize organically, but they are not foregone conclusions. The second category is *intentional lock-out*, which is considerably more insidious in nature but not any less common. This asserts that many of the reasons why a TIC can remain unchallenged for so long are due to the intentional actions of actors within the TIC. Here it must be pointed out that although these are avoidable actions under human control, they are no more preventable from outside the TIC than the inherent features of lock-out. A retrospective understanding of the cause-and-effect relationships between actions, their motivations and their outcomes from actors within the TTIC can help to inform policy both on how to break the current lock-in and how to mitigate it in the future.

3.1 Inherent Lock-out

Once a dominant design is selected, the lock-in and consequent lock-out effect is initiated at the firm level. The companies producing this hot product will continue to re-invest returns into refining this design and avoid investments in new options which could render their current products obsolete (Unruh, 2000). Their business purpose shifts from product innovation to process innovation and market analysis to gain a competitive advantage against other dominant design firms. They develop a set of core competencies and standardized procedures and then seek to incrementally develop them through efficiency improvements and quality assurance (ibid.). Workflows and knowledge then become siloed, leading not only to the lock-in of the firm but also of its employees. While this specific cascade of decisions perhaps cannot be considered inherent, the need for dominant design firms to compete amongst themselves certainly is. Technological progress can even lock out dominant design firms if they fail to keep up, and these methods (most famously, Toyota's *kaizen* method) have proven highly effective in staying ahead (Schilling, 2002). If an alternative technology were to become a worthy competitor, however, the incumbent firm's core competencies would then become core rigidities as divestment into the new technology would require a complete rehaul of its organizational structure (ibid.). For instance, there were countless examples of this during the digital revolution while the potential of the internet was slowly realized. A highly public case was the demise of Blockbuster and its inability to compete with Netflix and other online video services. Apparent core rigidity is prevalent in the auto industry as well, as in 2014 "electric car programs (or programs for any vehicle that doesn't burn hydrocarbons) at the major manufacturers are small to non-existent, constituting an average of far less than 1% of their total vehicle sales" (Musk, 2014). With the realities of peak oil and climate change looming, car companies should realize that the diversification of their fleet toward these technologies needn't be motivated by environmental sustainability, but of their own.

Instead, it would appear that firms operating in a sector characterized by network externalities often simply cannot envision anything other than a 'winner-take-all' market (Schilling, 2002). It has been empirically demonstrated that the selection of a dominant design is inevitably followed by an "industry shakeout" whereby firms producing alternative technologies are eliminated from the market (Unruh, 2000). Case in point, electric and steam cars were completely off the road in both the US and Europe by the 1930s. Concurrently, a shakeout also occurred within the ICE segment of the industry where in the 1890s there were 1900 firms producing ICE-powered vehicles in the US alone, but by the 1920s the 'big three' of General Motors, Ford and Chrysler commanded 90% of US market share and 80% of the global market (ibid.). This resulted in all the investment capital within the sector under control by the dominant design, and none of it was available for improving alternative technologies new or old. Financial lock-out of competitors is further compounded by the fact that financial institutions are understandably risk-averse in their lending habits and thus treat dominant design producers more favorably than unfamiliar technologies. Innovators are then left to seek investment from venture capitalists or government research grants, which come with greater stringency or higher costs (ibid.). These funding sources typically also place an emphasis on short-term returns, which both discourages risk-taking and deprives the technology of learning effects.

Not only are financial sources scarce for emerging technologies, human resources are as well. When a dominant design becomes entrenched within a techno-institutional space, the implications seep into the education system. New academic disciplines, such as automotive engineering and energy economics, are introduced to study the technology and prepare a workforce for the industry. This serves to reinforce the standards associated with the system as "rules of thumb" and to develop "orthodox" methods which facilitate the teaching process (ibid.). This quickly results in curriculum lock-in and instills the current dominant design as canon for the next generation. Many students and new entrants to the job market thereby lose a measure of autonomy in their career choice through no fault of their own. For those not locked in by curriculum - students of basic sciences, for instance - rational self-maximizing economic behavior dictates that they seek work within the dominant design technological system rather than an alternative, unproven one. This lock-in of the workforce thus locks out emerging technologies from the labor market. This greatly hinders their ability to build the capacity and accrue the talent necessary to advance along their technology's learning curve, let alone develop a curriculum to pass along.

The automotive and energy industries may be particularly susceptible to this type of lock-in due to their ubiquity and the complexity of the systems. It can take extraordinary dedication for an engineer to develop an expertise of the ICE or of deepwater extraction technologies, the end goal of which is to improve the performance of the current design and perpetuate its lock-in. The mastery of repair and maintenance techniques is also the life's work of many, and this trade has provided steady employment for some who lack access to skilled labor otherwise. This potential symbiosis was recognized early on by members of automobile clubs, who coordinated with the YMCA to start technical schools to train car mechanics (Unruh, 2000). This network of professionals becomes a self-sustaining institution supporting and dependent upon the dominant design technological system. Its permanence and societal influence grow even deeper when labor unions and industry associations are then formed, such as the Society of Automotive Engineers (SAE) founded in 1905 and the United Auto Workers (UAW) established in 1936. While these types of formal institutions are initially conceived to oppose the power of the firm over its workers, their interests "eventually merge with the interests of the oligopolistic dominant design producers as their common reliance on the continued expansion of the technological system becomes mutually obvious" (ibid.).

Here we can see that much of inherent lock-out is driven by existing societal institutions. They naturally support the dominant design as it diffuses by coevolving to preserve their own utility within society. Banks tend to avoid risky investments because they are built on public trust and thus need to preserve it. Universities need to attract students and ensure their employment to then attract future students, so they are obliged to cater to the dominant designs of the day. This coevolution also results in the emergence of new institutions surrounding the dominant design, such as curriculum and labor unions, and these begin to multiply in number and in value as the TIC grows. This self-perpetuating institutional lock-in creates circumstances which make it extremely difficult for alternative technologies to enter the market, but by conventional economic analyses it can ultimately be attributed to market forces. It would be incomplete but not incorrect to say that the ICE offered consumers desirable performance characteristics earlier and at a better price than the other propulsion methods, so the supply simply followed demand until market saturation. Since institutional forces are abstracted away in mainstream economics, their impact is confounded with the merit of the dominant design. The economic models upon which society bases their investment activity therefore propagates models with biased outcomes in favor of the established TIC (Unruh, 2000), inherently locking out the competition.

3.2 Intentional Lock-out

Despite these institutional forces naturally perpetuating the lock-out of their competitors, the actors at the helm of a TIC will often supplement them using the powers available to them. The lock-in of petroleum as the dominant fuel source for the ICE was explained earlier by circumstantial factors, the conglomeration of Standard Oil and the price difference. Of note is the absence of technical performance from that list, an issue which, along with price, should be paramount in a technological market. An interesting case was made at the time that perhaps gasoline was not even the clear victor in terms of price when all costs to the consumer were considered (Carolan, 2009). Gasoline poses a much greater fire hazard than ethanol because it is hydrophobic and lighter than water (alcohol is hydrophilic)[5], meaning that throwing water on a gasoline fire will actually spread the flame whereas it would immediately extinguish an ethanol fire. Insurance companies placed many restrictions on the storage of gasoline which did not apply to ethanol, and it is claimed that insurance premiums for gasoline motor vehicles were higher than if ethanol were used (ibid.). Though this may be trivial and certainly invisible to consumers at the time, the comparison of technical performance between the two fuels was a much more concrete debate and highly visible to the public through the media (Kovarik, 1998; Carolan, 2009).

The US Department of Agriculture (USDA), US Geological Service (USGS), US Navy and numerous private laboratories combined to perform thousands of tests comparing ethanol and gasoline performance starting in 1906 when the Free Alcohol Bill passed Congress (Kovarik, 1998; Carolan, 2009). The consensus was clear, and the better performer was ethanol for a variety of reasons on display in Figure 12. Some advantages are immediately evident, such as the smokeless and odorless emissions and the general cleanliness and quietness of operation (ibid.). Ethanol also has a higher octane content than gasoline, meaning that its "maximum power is usually materially higher," as reported by the USDA (Carolan, 2009). This also meant that a higher compression ratio could be achieved with ethanol, so not only can the engine produce more horsepower, it can also function more efficiently. This greatly diminishes gasoline's

[5] Hydrophobic means it is not soluble in water, and thus remain inflamed while floating on top unless a large volume of water is used. The difference in this chemical property between gasoline and ethanol is also the reason for phase separation.

perceived advantage of a 50% higher energy density[6] (meaning better fuel economy) because ethanol was shown to produce "highly comparable" gas mileage when the compression ratio is proportionally adjusted (Carolan, 2009). Lower compression ratios also produce "engine knock," audible and palpable secondary explosions within the cylinder which can damage the engine. Knocking is a frequent occurrence and major problem with pure gasoline but is nonexistent with ethanol (Kovarik, 1998; Carolan, 2009).

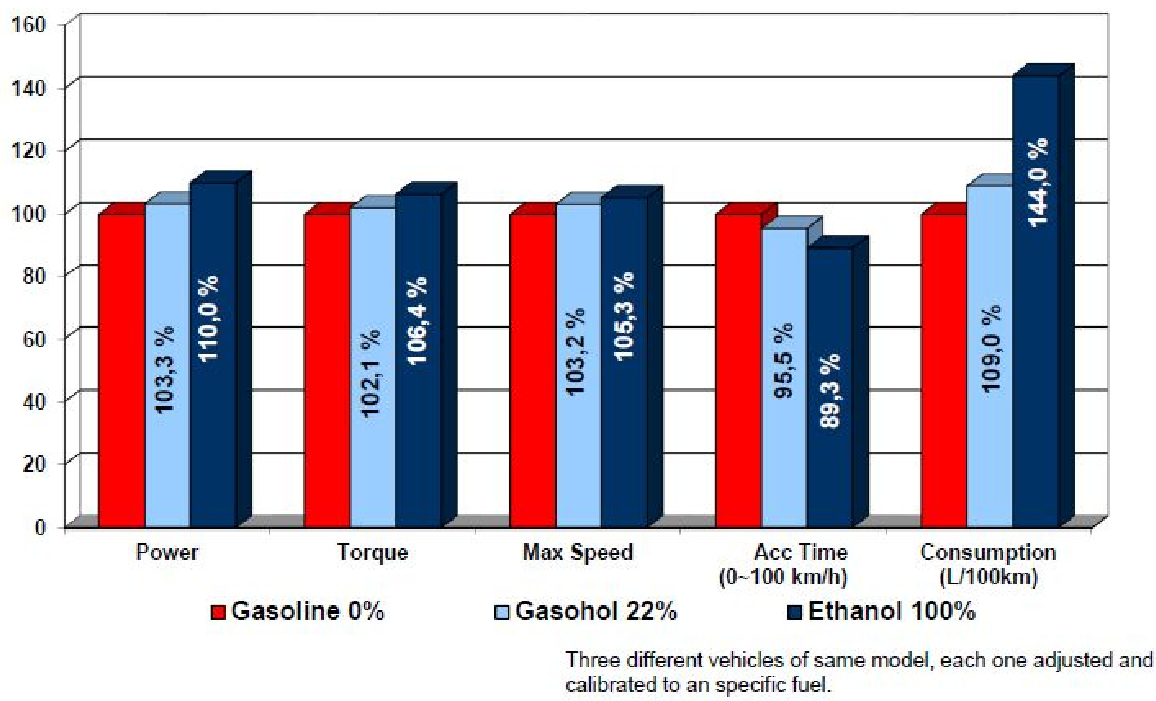


Figure 12. A 2013 study of flex fuel vehicles (FFVs) in Brazil which can run on gasoline, ethanol and any mixture of the two found ethanol to offer the best road performance in all categories except consumption (Joseph, 2013)

The early studies found one major performance drawback for pure ethanol - the difficulty of starting an alcohol-fueled engine at cold temperatures. This 'cold-start' issue could be easily remedied, some of the studies reported, by blending in a small amount of ether with the alcohol (Kovarik, 1998). An electric heater has been designed to address this issue for modern ethanol-based engines, so the additive is no longer necessary (Kabasin, Hoyer, Kazour, Lamers, & Hurter, 2009). Many of the early studies also included gasoline-alcohol mixtures (gasohol) in their experiments, and this introduced another problem called 'phase separation'. When alcohol

[6] 120,000 BTU per gallon compared to 80,000 BTU per gallon for ethanol

and gasoline are blended together in the presence of water, they begin to separate from each other and form a heterogenous mixture. However, this could be avoided by adding small amounts of benzene (Kovarik, 1998), and improvements to distillation methods would soon produce 'anhydrous ethanol' completely absent of water content, resolving this issue even more cost effectively (Carolan, 2009). These blended fuels garnered a lot of attention and praise because they solved all the shortcomings of gasoline - gasohol boosts octane content and eliminates engine knock - without the price tag of pure ethanol. In 1925, a prominent chemical engineer M.C. Whitaker expressed his sentiment, "Alcohol blends easily excel gasoline on every point important to the motorist. The superiority of alcohol fuels is now safely established by actual experience" (Kovarik, 1998; Carolan, 2009). Similar results were reported from studies conducted throughout Europe, and this sentiment was echoed throughout the international media and automotive magazines in the first three decades of the century (ibid.).

Indeed, ethanol had a powerful ally in the automobile industry throughout the early part of the 1900s when the ICE was still in competition with electric and steam vehicles. They had a keen interest, then, in assuring the finest quality performance from their product, and that was largely dependent on the fuel choice. GM was very active in conducting their own studies on the subject, and these came out very much in favor of ethanol and gasohol over gasoline (B. Kovarik, 2009). These studies, led by Charles Kettering, were equally concerned with the continued success of the car industry into a future rife with uncertainty concerning oil supply. Kettering's team openly deemed alcohol the "fuel of the future" but were also calculating (mistakenly) that it would require over half the country's farm area to produce the amount of ethanol necessary for the vehicle fleet (Kovarik, 1998). Apparently they did not account for the fact that the grain used for alcohol fermentation (called distiller's grain) is actually the preferred source of livestock feed, so it is entirely recycled and there is theoretically zero loss in food value (ibid.). In any case, their findings led them to investigate cellulosic ethanol production, which they found promising but the cost was excessive at the time (ironically, we find ourselves at the same juncture with these "second generation biofuels" one century later) and GM's research focus would soon after shift drastically.

In 1921, the same researchers stumbled across a metallic additive for gasoline which would impart the same octane boosting, knock-reducing properties as ethanol - tetraethyl lead

(TEL). Kettering continued to research ethanol production after this discovery, but GM soon realized that "leaded gasoline possessed one important property that alcohol did not: it could be patented" (Carolan, 2009). They projected that this would give them a 20% share of all gasoline profits, which would be worth billions by the 1950s (Kitman, 2000; Carolan, 2009). Kettering and company suddenly changed their tune in 1924, stating that, "So far as science knows at the present time, tetraethyl lead is the only material available which can bring about these [antiknock] results" (Kovarik, 1998). Not only were these statements about its technical superiority false, so was their eventual claim that it cost less than gasohol. The only unique advantage of TEL was its profitability. Later that year, GM teamed up with Standard Oil Company of New Jersey (later to be renamed Exxon) to create Ethyl Gasoline Corporation (Ethyl Corp), the exclusive owner of leaded gasoline or, as they marketed it, "ethyl gasoline" technology. And so the TTIC familiar to us all today was officially created through the marriage of one of the world's largest automakers and one of its largest oil refiners over their common interest in poisonous, liquefied lead.

Just to be clear, the dangerous neurotoxic effects of lead were well recognized at the time, and had been for 3,000 years (Kitman, 2000). DuPont company, which was manufacturing TEL for GM, described it internally even before the patent was filed as "a colorless liquid of sweetish odor, very poisonous if absorbed through the skin, resulting in lead poisoning almost immediately" (ibid.). This was repeatedly denied to the public and to the government, however, and leaded gasoline hit the market with far greater success than imagined (Kitman, 2000). By the 1936 about 90% of all gasoline in the US was leaded, and it remained the dominant design for decades until it was outlawed in 1986 (Kovarik, 1998; Kitman, 2000; Carolan, 2009). Retrospective studies have shown that the average blood lead concentration among Americans was 16 μg/dL in 1976, compared to the accepted maximum "safe" level of 10 μg/dL and the average concentration of 3 μg/dL in 1991, five years after the ban was imposed (Kitman, 2000; Reyes, 2007). The rampant lead poisoning has been linked to high crime rates, lowered IQ across the population and 5,000 deaths per year (ibid.). The fact that Ethyl Corp was able to convince the public to use this product against their own common sense and to the detriment of their own health is a sobering indication of the power held by the TTIC. Figure 13 provides a glimpse at how successful both the auto industry and the oil industry had become by the time they discovered TEL, and how quickly they grew (notice the similar shape to the "increasing returns" half of Figure 8). With the partnership of DuPont, this meant that three of the world's largest corporations had a vested interest in locking in lead-laced gasoline and the intentional lock-out of ethanol. They were each at the center of formidable webs of network externalities that extended into the government and the media, the most direct routes to institutional influence.

Evidence of this has been gathered from Du Pont's successful cover-up of lead poisoning-related deaths of workers at its first TEL plant, and from Ethyl Corp's contract with the US Bureau of Mines (a governmental regulatory body) to perform studies on TEL explicitly to "refute any false propaganda" and which could not be released without Ethyl's approval (Kitman, 2000). At least 13 more workers died and hundreds fell ill of lead poisoning at TEL manufacturing plants in the next two years (ibid.), but Ethyl Corp was cleared of all charges and leaded gasoline was permitted to remain in the market under the supervision of the Public Health Service (PHS). Directly responsible for the oversight of the PHS, however, was Treasury Secretary Andrew Mellon, whose family controlled Gulf Oil and was recently granted an exclusive partnership with Ethyl to distribute leaded gasoline (ibid.). The top executives of Ethyl, including Charles Kettering and its president Earle Webb, had also gone out of their way to develop a personal rapport with Surgeon General H.S. Cumming , and in 1932 the du Pont family changed party alliances to provide promising candidate Franklin D Roosevelt a hefty contribution to his campaign finances (ibid.). None of the government-funded studies on TEL toxicity promised in the 1925 court hearing were ever commissioned, and instead all the official public knowledge on the topic was reported by Ethyl Corp and its close associates (Kovarik, 1998; Kitman, 2000). When British scientists reported in 1928 on the "slow, subtle, insidious saturation of the system by infinitesimal doses of lead extending over a long period of time" due to leaded gasoline emissions, US Surgeon General Cumming personally contacted England's Ministry of Health to ensure TEL would be declared safe for the British market (Kitman, 2000.). Similar anecdotes have been recorded about Cumming's influence in France and in Switzerland (ibid.).

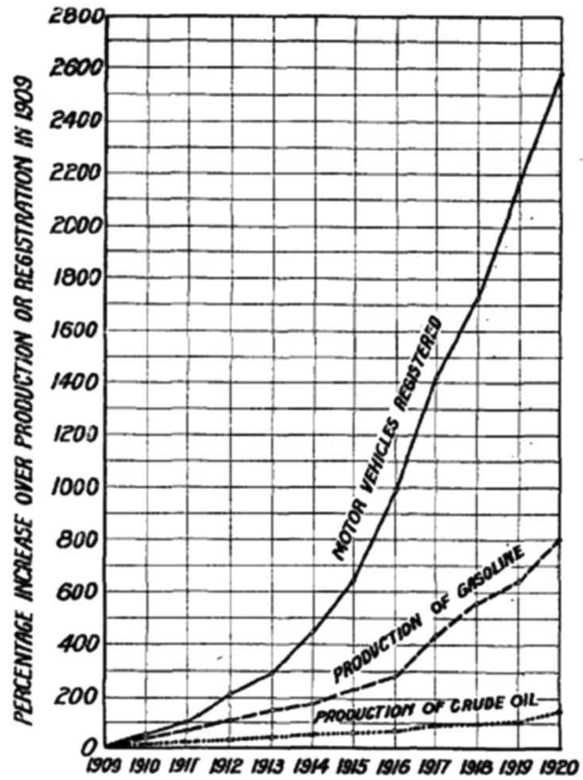


Figure 13. Graph from a 1921 report showing the rapid growth of the US car and gasoline markets in percentage growth from 1909-1920 (Carolan, 2009)

Cumming's exact motivations for such involvement is unclear, but his influence abroad would prove very significant for his puppeteers' aspirations for intentional lock-out. Most of Europe was already flooded with US-controlled petroleum from WWI military needs, and the supply simply continued thereafter as civilian energy demand increased. However, the war also heightened concerns over the reliance on foreign oil, and almost every European government passed legislation to support alcohol production by the 1920s. This government intervention on national security grounds built a foundation for an ethanol TIC to arise, and gasohol had become the standard transport fuel in every industrialized nation (Kovarik, 1998). Some nations, such as France, Germany, Italy, Poland and Hungary mandated the blending of alcohol into all gasoline sold in the country (ibid.). France accomplished this by both forcing gasoline importers to purchase ethanol from the state monopoly for blending (10% at first, then up to 25% in 1928) and imposing a tax on gasoline to subsidize the alcohol (ibid.). Oil companies objected at first to the mandatory blending laws, but alas they could not achieve the political influence that they had in the US and could not afford to lose the European market to competitors. Thus it became standard business practice, evidenced by Standard Oil financing Poland's state alcohol monopoly with a 5-year advance purchase of blending volumes (Kovarik, 2013). Other countries, such as Britain, Czechoslovakia, Greece, Switzerland and Sweden opted to subsidize alcohol production through tax incentives (Kovarik, 1998; Carolan, 2009). This proved so effective in Greece that the government later had to revert to an ethanol tax to recover lost petroleum tax revenue (Carolan, 2009).

These policies enabled the alcohol fuels industry to accrue learning effects throughout the interwar period. Ethanol plants were able to handle a seasonal rotation of surplus crops from grapes to potatoes to maximize economic efficiency (Kovarik, 1998). Sweden was already fermenting paper mill waste to produce alcohol, which was blended at 25% with petrol imports (ibid.). As early as WWI, France had begun research on algal biofuels, extracting ethanol from kelp (ibid.). Germany's behemoth firm I.G. Farben (with whom Ethyl established a partnership in 1935 for constructing TEL plants in Germany) had invented a technique for cheaply producing methanol from coal, and this became a popular gasoline additive across Europe as well (O'hanlon, 1984); Kovarik, 1998; Kitman, 2000). British engineer of the Rolls Royce engine H.R. Ricardo designed a new racing fuel made of ethanol, methanol and acetone which would be widely used internationally (Kovarik, 2013). Ethanol consumption reached a peak in the mid 1930s in both Germany and France, but a poor harvest in 1937 and 1938 followed by a shift from alcohol production to ammunition during WWII led to the disappearance of many government biofuel programs (Kovarik, 1998). Thanks to the US government's help, Ethyl Corp could come fill the gap with leaded gasoline. Once again, American oil would profit mightily from the bloodshed (on both sides, due to the continued business alliance with I.G. Farben), and this time bullets would not be the only lead filling the air. The European ethanol industry would not recover following the war, in large part because oil represented 10% of the entire expenditure - the largest single commodity - of the Marshall Plan (Painter, 1984).

Ethanol also staged a resurgence in the US during the 1930s as farmers hit by the Great Depression found their own political platform from which to propose legislation, the Farm Chemurgic Movement. Eight states saw over three dozen proposals for ethanol tax incentives and blending mandates, and a gasohol blend named Agrol became available at 2,000 gas stations across the Midwest by mid-decade at the same price as leaded gasoline (Kovarik, 1998). However, unlike in Europe, the oil industry would be able to respond with its political and societal influence. The American Petroleum Institute (API) sent memos to its members in 1933 to form state-level "emergency committees" to oppose the subsidies and then initiated a "coordinated program to be connected throughout the industry" (ibid.). A propaganda campaign was launched throughout the Midwest, spreading sabotaged scientific reports and fear-mongering messages playing on financial hardship (see Figure 14) and Prohibition sentiments[7]. The chemurgists pointed to the government's own projections that domestic oil reserves would be depleted within 17 years, but by then "the petroleum industry's estimates were given greater weight by policy makers and the public," and these of course pointed to an "almost limitless" supply (Carolan, 2009).

By the end of the decade, only three states had passed tax subsidies for ethanol - Iowa, Nebraska and South Dakota - and nothing was passed at the national level (Kovarik, 1998). It has since been revealed that the API spent $100,000 on efforts to overturn those three 'losses,' which proved successful in Iowa (Carolan, 2009). They had also made large contributions to automobile clubs, state and federal Congressmen and departments of the federal government during that time (Kitman, 2000; Carolan, 2009). Perhaps not so coincidentally, the Federal Trade Commission (FTC) issued a restraining order at Ethyl Corp's request in 1936 to prevent competing firms from publicly criticizing Ethyl's toxic gasoline in advertisements (Kovarik, 1998; Kitman, 2000). Pro-gasohol politicians and businessmen also reported being harassed and spied upon by the API and associates (Kovarik, 1998; Carolan, 2009). Another covert tactic by Ethyl Corp was to suddenly enforce a "business ethics" standard as to which gasoline wholesalers could obtain licenses for distribution of their product, the holder of a 90% market share (ibid.). As the Supreme Court would eventually rule in 1940, they obviously used this maneuver to discriminate against distributors of ethanol blends, but anyone who didn't comply was long gone from the market by 1940 (ibid.).

[7] A notorious quote from a popular API-funded radio show host: "alcohol in motor fuel would be to make every filling station and gasoline pump a potential speakeasy" (Carolan, 2009)

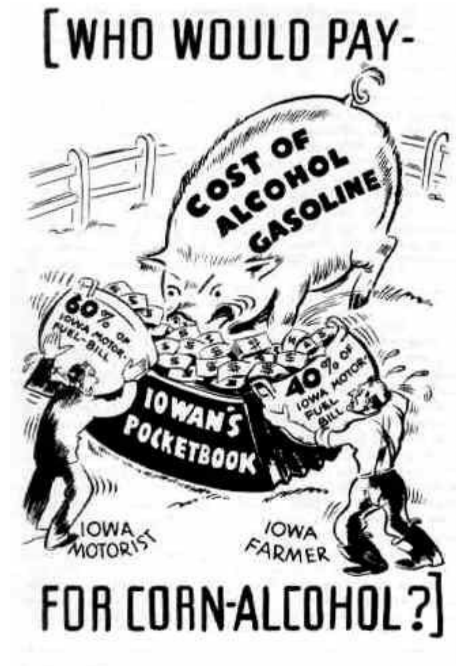


Figure 14. Propaganda poster found in Iowa circa 1933, where an ethanol tax subsidy for farmers was overturned by the Supreme Court (Kovarik, 1998)

American society has long criticized how state or public ownership of monopolistic enterprises can kill innovation in favor of rent seeking and political objectives. However, the TTIC demonstrated how government agents can be captured in a capitalist democracy to the exact same effect, such that the lock-out of competitors becomes the interest of the government. Intentional actions by the government are capable of overriding market forces to favor the lock-in, and these behaviors can in turn become locked into government policy and functionality. To mince fewer words, the corruption of government officials through financial or personal influence can become institutionalized in a capitalistic democracy, and such is the case in the United States. A 2016 study by UK-based non-profit InfluenceMap was not shy about this assertion either after unearthing $114 million spent on lobbying against climate change legislation by just 5 petroleum organizations in 2015 (see Figure 15), and concluded that "it is not unreasonable to estimate that in excess of $500m is spent by the corporate sector globally on obstructing ambitious climate policy and regulations in line with achieving less than 2C warming" (InfluenceMap, 2016). Furthermore, the researchers disclosed that this estimate does not include the "dark pools" of money from oil companies into SuperPACs[8], think-tanks and

[8] Super Political Action Committees, or massive political influence groups which are not required to disclose their donors according to the 2010 'Citizens United vs. US Supreme Court' ruling.

astroturf organizations[9] which fuel the US climate change denial machine (see Appendix II).

Private interests who establish a dominant design are then incentivized to exploit this institution by prioritizing political and regulatory management competencies over innovative capacity (Unruh, 2000). This is facilitated by weak lobbying regulations which permit the 'revolving door' effect, meaning that government members, immediately after leaving office, are legally permitted to accept employment in industries which had funded them throughout their tenure. Not only does this provide firms with an incredibly effective bribery tool, it graces them with the best lobbyists money can buy - policy experts with insider connections and influence. This describes an extreme form of lobbying which can be used by firms to gain a relative advantage in the market (e.g. by securing government contracts) or by industry representatives to promote or reinforce the lock-in of their technology (e.g. through subsidization). In the case of Ethyl Corp and API, considering that the competing technology consisted only of 10% ethanol and 90% their own product, the unmistakable goal was to intentionally and entirely lock ethanol out of the fuels market.

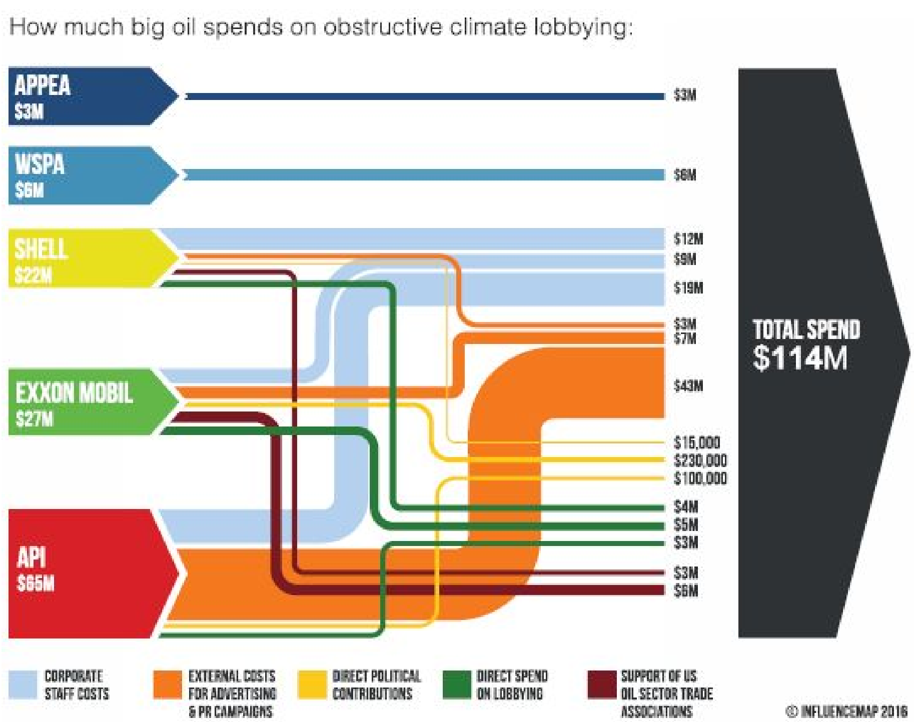


Figure 15. Graphic breaking down the estimated anti-environmental lobbying budget of 5 large petroleum organizations in 2015 (InfluenceMap, 2016)

[9] Astroturf campaigns are designed to mask the identities of the financiers and thus appear indistinguishable from grassroots political movements to its members, the public and the media.

Chapter 4. The Techno-Institutional Path to Sustainable Transport

4.1.1 United States

The early history of motorized transport serves to show that the modern reality of a petroleum dominated transportation sector was not the market-driven certainty that it is assumed to have been. The technological selections of the ICE and gasoline were not driven by technical performance nor by consumer preference. To a large extent they were chosen for economic appeal, but this was owing to fortuitous circumstances and idiosyncrasies characteristic of path dependence theory. Their successful lockout of competing technologies then allowed the TTIC to enjoy decades of infrastructural, technological network, political, institutional behavioral lock-in to the point where the alternative options became a forgotten piece of history to the general public. It has not been forgotten to science, however, and technological improvements to EVs, ethanol and other biofuels represent today's easiest possibilities for the inevitable transport fuels transition. Major research and development in these fields finally resumed in the US when the oil shocks of the 1970s crippled the world economy.

In 1976, the Electric and Hybrid Vehicle Research, Development, and Demonstration Act initiated a five-year $160 million government spending program to jumpstart EV technology. The official bill sent to President Gerald Ford's desk described very succinctly the lock-out effect they were witnessing in the transportation industry: "Without Federal assistance, private industry will move slowly in developing and demonstrating these vehicles because of (a) the high cost and risk involved, (b) the investment by major automobile manufacturers in the internal combustion engine, and (c) the absence of private capital markets" (Cannon, 1976). Ford apparently was not as concerned with this matter and vetoed the bill, only to be overturned by Congress. Alas, EV technology could not be developed to a competitive state in those 5 years, suffering from limited range and power, and the program would not be renewed. In the meantime, government support for a petroleum alternative - the more obvious approach in an oil crisis - was glaringly absent. Unsurprisingly, lobbying and propaganda from the API was back to peak form, using recycled false accusations of ethanol's technical disadvantages (Kovarik, 2013). It was not until late 1980, almost two years after the Iranian revolution in January 1979, that President Jimmy Carter was able to pass a tax incentive for ethanol of $0.54 per gallon (ibid.).

In a classic turn of path dependence, another important development had just concluded at the time of the 1973 oil embargo, without which these programs may not have been possible. The anti-air pollution movement of the 1960s culminated in a 1969 government lawsuit against the four major car companies (GM included) for conspiring to delay market-ready pollution control technology (Kitman, 2000). Beginning in 1974, all new cars were to be fitted with catalytic converters to trap pollutants responsible for smog and acid rain (ibid.). Purely by coincidence, the platinum-based device (and the car) ceases to function when exposed to lead. The existence of this technology may provide some explanation for why GM and Standard Oil suddenly decided to sell Ethyl Corp in 1962 to Albemarle paper manufacturing company, thus officially separating the two power players of the TTIC (ibid.). The divorce was complete in 1970 when GM decided to submit to the court ruling rather than to fight it (ibid.). TEL would be phased out by 1986 in the US, at which point Ethyl and other refining companies replaced it with other oil-derived octane-boosting chemicals - most notably methyl tetra-butyl ether (MTBE) - which were all soon proven to also be toxic (Kitman, 2000; Kovarik, 2013).

Figure 1.1 | RFS2 original mandates by biofuels category

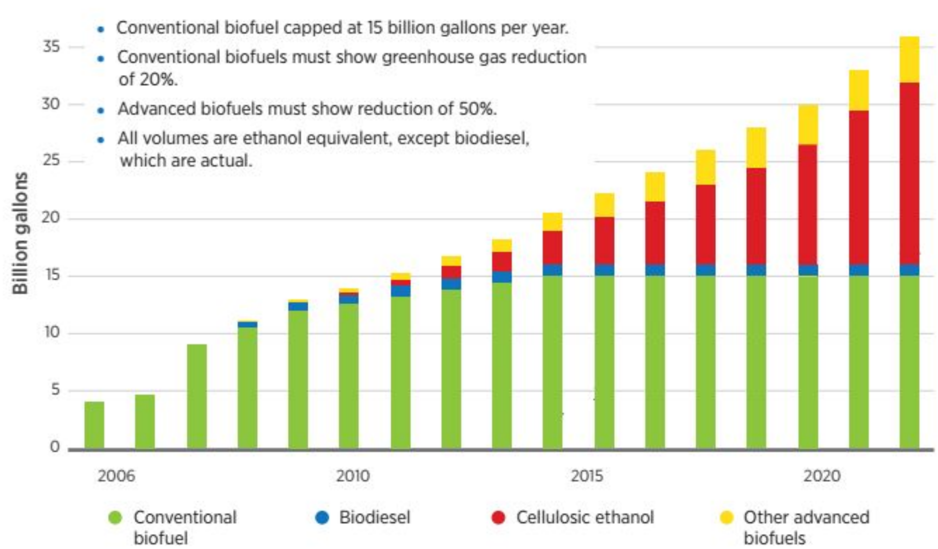


Figure 16. Projections from the RFS2 in 2007 for the growth of biofuels in the US until 2022 (Langholtz, Stokes, & Eaton, 2016)

The century-long lock-out was finally broken by the convergence of policy and science in 2005 when the Energy Policy Act and its Renewable Fuel Standard (RFS1) program mandated ethanol be used as an octane boosting gasoline additive. The target was set to produce 7.5 billion gallons per year by 2012, which would account for approximately 5% of the total transport fuel consumption in the country (Langholtz et al., 2016). While this was a major first step - its impact on annual motor fuel consumption is clearly visible soon after 2005 in Figures 4 and 17 - it would not even be a sufficient blend volume to produce the octane rating of leaded gasoline without additional chemicals. In 2007, the Energy Independence and Securities Act (EISA) addressed this issue and set even higher blending targets with the RFS2. Today, virtually all gasoline sold in the country is a 10% ethanol blend (E10) with equal performance to Ethyl Corp's leaded variety (ibid.). The US is actually the current world leader in ethanol production, outputting 14.1 billion gallons in 2014 (ibid.), but in historical terms this only puts us where we should have been in 1930, effectively erasing the lock-in of TEL.

The RFS2 has set another lofty goal of 36 billion gallons of biofuel by 2022, which would represent approximately 25% of the transport fuel currently consumed in the US each year (ibid.). If this 21.9 billion gallon (or 155%) increase can be achieved in the next five years, then it would truly begin to challenge the lock-in of oil in the TTIC. Increasing returns principles would dictate that this is a real possibility, but another stipulation of the RFS2 is that conventional crop-based ethanol (i.e. first generation biofuels) shall be capped at 15 billion gallons (for sustainability reasons to be explored later this chapter), which is estimated to have been reached by 2016 (ibid.). This means that the 21 billion gallons will have to be comprised of the much less developed cellulosic ethanol (second generation) and other advanced (third generation) biofuel technologies, which in 2014 reached production values of 728,000 gallons and 12 million gallons, respectively (ibid.). Figure 16 shows that these are both well behind the original projections from the EISA, but the models employed predict a linear growth pattern which does not account for increasing returns. 36 billion gallons therefore remains an attainable goal with coordinated efforts within the industry, with supporting industries, from the government and from society, but it is crucial to success that this techno-institutional change is well-informed by the nation's institutional pressures, explored below.

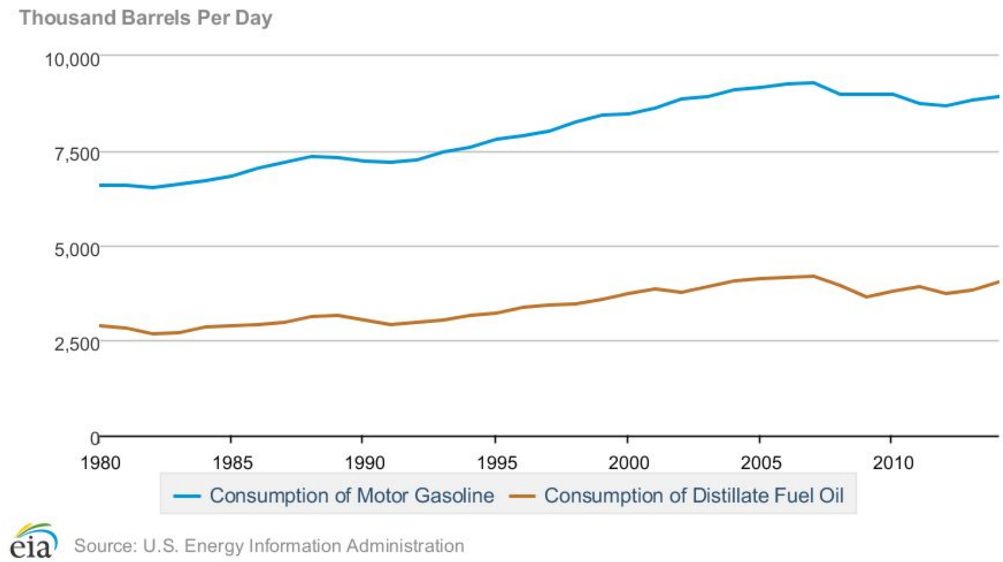


Figure 17. US consumption of gasoline and diesel (distillate) fuel from 1980 (6.58 million bbl/day) to 2014 (8.92 million bbl/day); latest data shows that the number was 9.33 million bbl/day in 2016 (EIA, 2017b)

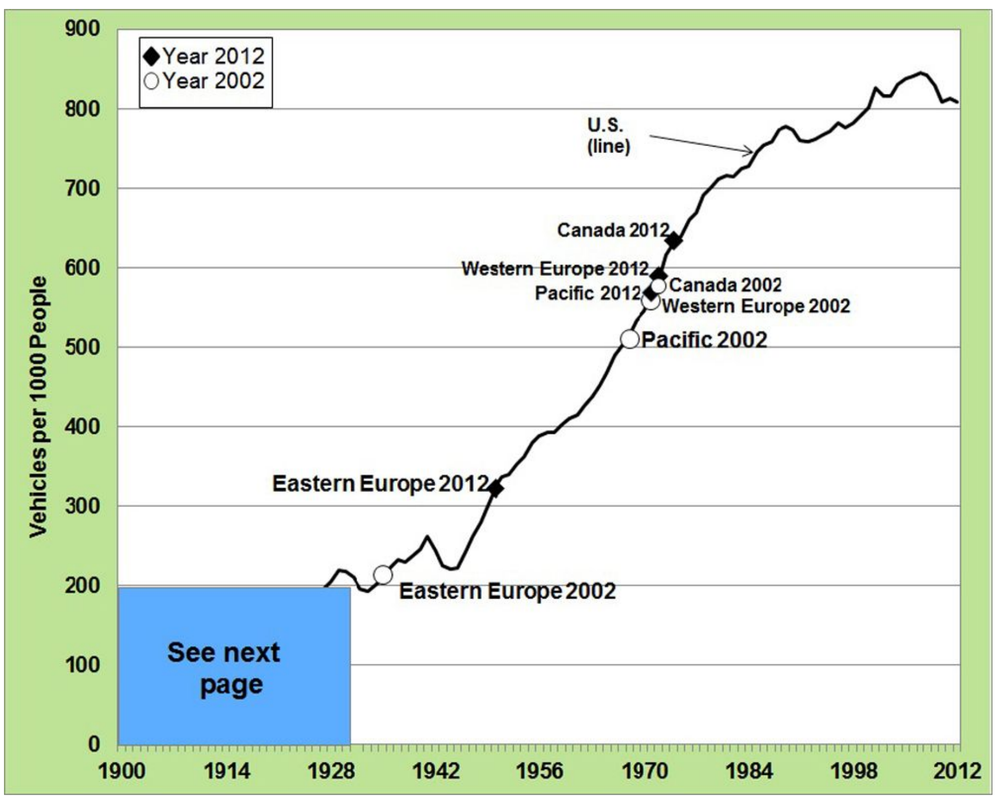


Figure 18. The number of cars per 1,000 people in the US from 1900 - 2012 (represented by the line) compared to the number of cars in other regions in modern times (EERE, 2014)

As a relatively young, sprawling nation priding itself upon innovation, individualism, freedom and economic prosperity, American society readily evolved to develop its culture around the motor vehicle. Indeed, the USA is perhaps most classically stereotyped by its obsession with the car, and many of the institutions surrounding transportation lie at the nation's core. In 2016, the United States consumed 391.73 million gallons of finished motor gasoline each day, amounting to an astronomical 143.37 billion gallons that year (EIA, 2017a). For a population of 326.6 million, this means 439 gallons of gasoline per capita each year, and this doesn't even include the approximately 4 million barrels of distillate fuel oil (primarily diesel) that the US consumed each day in 2014 (see Figure 17) (EIA, 2017b). This is largely due to the fact that Americans own the most personal vehicles per capita in the world at 807.99 per 1,000 people, as depicted in Figure 18 (EERE, 2014). Another major culprit for this extravagant consumption is that America is home to the least efficient vehicle fleet in the world, burning an average of 9.1 Lge/100km (liters of gasoline equivalent per 100 km) (see Figure 19). In an interdependent web of cause and effect, there are both political and societal institutions which can explain why this is.

The most concrete explanation is that the United states enjoys the "lowest price for gasoline and diesel for any advanced economy" according to a study on fossil fuel subsidies by the European Commission using statistics from the International Monetary Fund (IMF) (Bárány & Grigonytė, 2015). Fossil fuels subsidization is notoriously difficult to track due to the many avenues through which benefits can flow from a government to the energy sector, but IMF estimations indicate that the US is the largest fossil fuel subsidizer in the world (ibid.). Pre- and post-tax subsidies in 2011 totaled 410 billion USD, equal to 2.8% of the nation's GDP, the second highest ratio of any developed country behind Luxembourg (ibid.). As can be seen in Figure 20, subsidies for oil alone account for almost 60% of the total, or $246 billion per year (ibid.). These figures also cannot fully account for the lost revenue in unpaid taxes by oil firms. The Institute on Taxation and Economic Policy (ITEP) found that the oil, gas and pipelines industry collectively paid an effective tax rate of 11.6% on their *reported* earnings between 2008 and 2015 - 23.4% lower than the 35% US corporate tax rate - but it is an open secret that billions in revenue are hidden in offshore tax havens through mechanisms both legal and otherwise (Gardner, McIntyre, & Phillips, 2017).

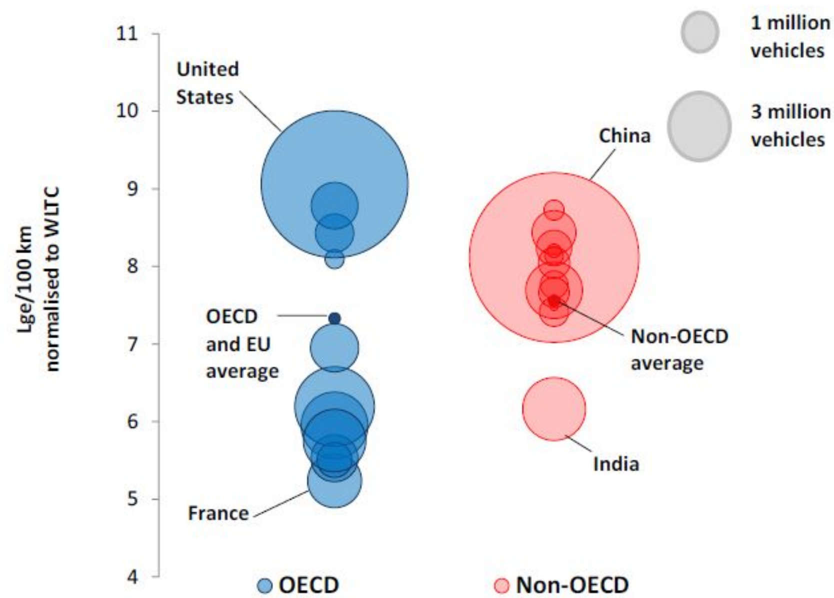


Figure 19. Average fuel economy of new vehicles sold in 2015 across selected countries in Lge/100km (IEA, 2017b)

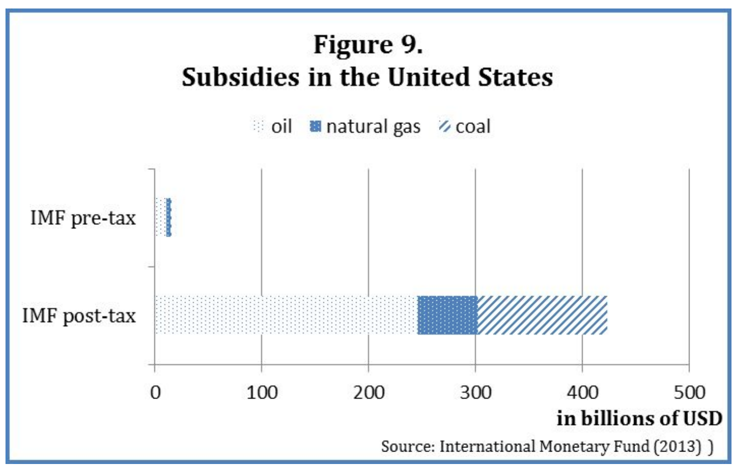


Figure 20. IMF estimates of the subsidies granted to the fossil fuels industry by the US government in 2011, both pre-tax and post-tax (Bárány and Grigonytė, 2015)

These enormous subsidies result in market distortions so strong that they could alone explain the lock-out effect. An alternative technology would effectively need to overcome a $246 billion annual sunk cost to the nation for it to be an attractive option. The extremely low price of gasoline relative to other nations with comparable GDP drives a higher relative demand, translating to a lower consumer demand for alternative fuels or fuel efficiency. This is then further compounded by 'truck culture' and 'SUV culture,' the consumer taste for pickup trucks, sport utility vehicles and other large vehicles among major demographics. As indicated in Figure

21, the US ranks a very close second to Canada for the largest average vehicle size in the world (Bárány and Grigonytė, 2015). There are practical reasons for large vehicle ownership - heavy duty trucks for work or towing purposes, SUVs for storage capacity and traction in snow, minivans for large families, etc. - but the primary reasons are cultural. For example, the idealization of suburban life was a societal institution that coevolved with the car, and today that has resulted in 'Walmart culture' and large shopping centers, malls and outlets positioned along highways. Otherwise known as the 'disappearance of Main street,' most people need to travel much greater distances now to purchase essentials, and this has fostered a 'buy in bulk' mentality which feeds the need for larger cars. Furthermore, cars are often not simply a mode of transportation but a status symbol and an expression of personality. One of the most culturally reinforced characteristics in the US is strength, and this has been obviously projected through automotive design since the arrival of American muscle cars. Today, this is manifested in pickup trucks among rural populations particularly in the South, and in SUVs among urbanites and suburbanites. Correspondingly, there exists a palpable social pressure discouraging people from choosing small, fuel efficient cars just as the quiet, clean EV of yesteryear was socially constructed as a woman's car. So perhaps these tastes were not born from the heavy gasoline subsidization, but these lifestyle institutions are clearly enabled by cheap fuel.

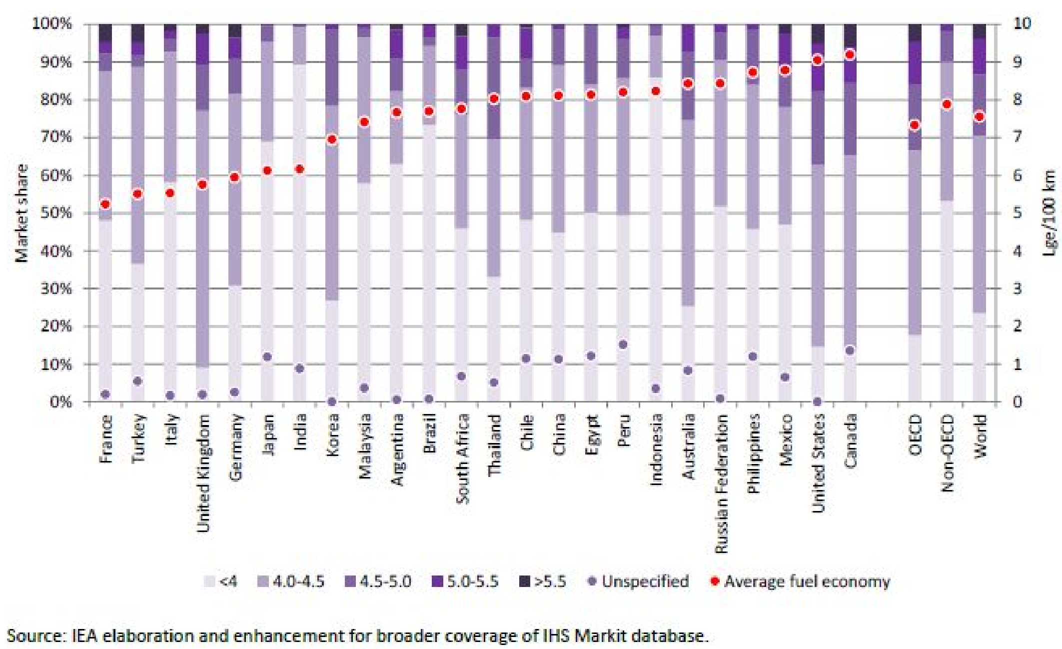


Figure 21. New passenger vehicle size (indicated as 'footprint' classes from <4m^2 to >5.5m^2) by country (Bárány and Grigonytė, 2015)

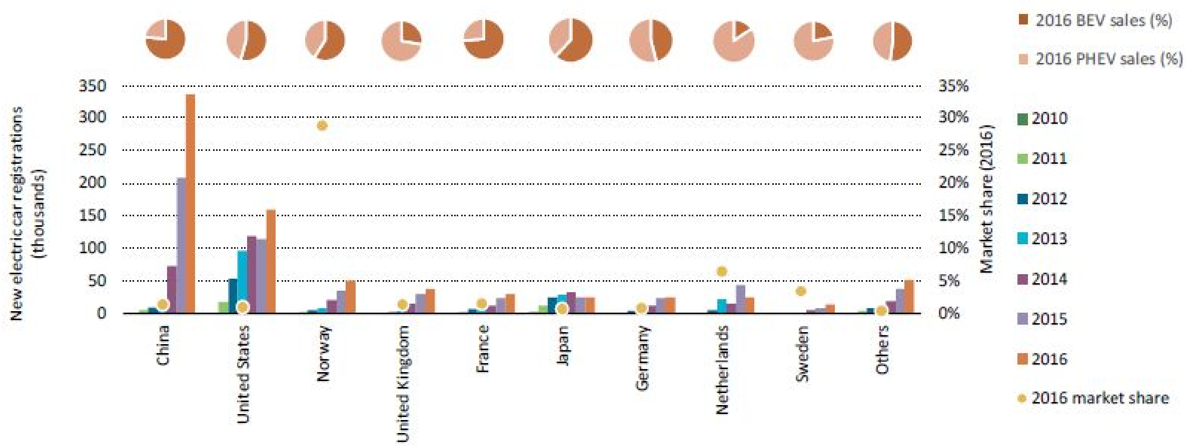
The classical justification for subsidizing fuel is to declare it a basic need and to thus control the price to a level where everyone can access it, which is why it is such a common policy in developing nations (Bárány and Grigonytė, 2015). This argument does hold some water for transportation fuel in the US, where driving is a daily activity for the majority of the workforce and where rapidly increasing property values in many urban areas has forced poorer communities further away from employment opportunities. The public transportation system in the country has been in decline for decades (popularly attributed in part to another GM-and-Standard-Oil-led conspiracy to buy up and replace the beloved electric streetcar systems and with buses), and particularly lacking are connections in a suburban sprawl (O'Hanlon, 1984). By the same reasoning that deters people from fuel efficient vehicles, bicycles and mopeds are stigmatized in many urban communities where they would be sensible. However, while these may be valid reasons for government assistance in personal transport, heavy gasoline subsidies at the pump have been proven to be the most regressive form of subsidy (Bárány and Grigonytė, 2015). Simply, the people who benefit the most from this program that everyone pays for are the ones who use (read: can afford) the most gasoline. More equitable support mechanisms would be targeted subsidies to the lowest income brackets for those who can prove the need for car use to continue their livelihoods, through tax breaks or voucher programs for instance.

However, these subsidies are so deeply institutionalized in American society that a president's performance is frequently judged by the gasoline prices throughout his tenure, despite them of course being entirely out of his control (Harbridge, Krosnick, & Wooldridge, 2014). Therefore, a removal or even an ill-timed cutback on fuel subsidies would equate to political suicide. The IMF estimates that complete elimination of the $2 trillion in fossil fuel subsidies worldwide would decrease global emissions by 15-23% (Bárány and Grigonytė, 2015). Building upon this logic, removing the $246 billion petroleum subsidy in the US would result in an approximate 2-3% reduction in global GHG release. While certainly of significance, this indicates that the 'reduce' route (i.e. conservation) is not as critical as the 'replace' route (i.e. transition) for decarbonization when it comes to energy consumption. This concept can also be extended to fuel subsidy strategies. In the institutional context of the US, it may be more prudent in terms of both climate preservation and realpolitik self-preservation to maintain a similar amount (in absolute terms) of transportation subsidization in the short term, but to transfer them to sustainable biofuels. In other words, as more biofuels are phased in, the reduction in gasoline consumption will directly result in a decrease in gasoline subsidies. These savings should then be spent on subsidies for biofuel consumption such that the end-user cost of fuel per mile driven should not increase noticeably. This policy strategy would serve the dual purpose of unlocking the petroleum TIC while building an institutional structure around advanced biofuels technologies, thereby fostering new techno-institutional complexes.

A portion of the saved subsidies could also be redirected to EVs depending on the economic performance of biofuels and the global oil market price, although the government has already established the Qualified Plug-In Electric Drive Motor Vehicle Tax Credit in 2009 to provide a tax rebate to purchasers of new battery EVs (BEVs) and plug-in hybrid EVs (PHEVs) (EERE, 2017). The private sector in EV technology, unlike biofuels, has also been highly visible to the public in recent years. In particular, Tesla Motors is proving to be an exception to the rule of financial and labor limitations which propel the inherent lock-out of alternative technologies. Its founder and CEO Elon Musk accrued a fortune through his previous entrepreneurial efforts and thus commands his own investment capital along with the trust of external investors. This gives him the liberty to take calculated risks, which he used immediately by entering the market in 2008 with the $100,000+ Tesla Roadster supercar. This was a unique business strategy for an automobile startup - or any startup - to say the least, but it proved to be a stroke of marketing genius that demanded the attention of a worldwide audience. The company is now hoping to capitalize on this market presence with mass production of its $35,000 Model 3, which will be widely available in 2018 and has long sold out of pre-order stock.

Another risky maneuver was his decision in 2014 to go "open source" by sharing his patents with anyone who wishes to use Tesla technology "in good faith" (Musk, 2014). Acknowledging the need to break the curriculum and workforce lock-in, he wrote in his Tesla blog that "technology leadership [is defined] by the ability of a company to attract and motivate the world's most talented engineers." (ibid.). He claims to have made this decision after witnessing the inertia of the major auto manufacturers - exhibiting their core rigidities - during Tesla's first 11 years. This "unfortunate reality," in his words, led to the realization that EVs would have a miniscule impact on the carbon lock-in at the current rate of adoption.

Emphasizing the need for a “rapidly-evolving technology platform” (ibid.), Musk is embracing an opportunity to manufacture increasing returns through learning effects early on in the development of the modern EV industry. On top of this, Model 3 sales should easily eclipse the 155,000 sales this year (see Figure 22) and allow Tesla to capture increasing returns to scale beginning next year. Furthermore, the company’s patents also include infrastructural technologies such as charging stations and household solar roofs with battery storage, so a positive feedback loop may be extended through network effects. Despite constant criticism from economic analysts and operating at a net loss since deciding to open the patents, Tesla appears poised to lead an EV boom in the near future, espousing path dependency mechanisms to challenge the ICE TIC and establish an EV TIC (see Figure 32).



Sources: IEA analysis based on EVI country submissions, complemented by EAFO (2017a), IHS Polk (2016), MarkLines (2017), ACEA (2017a, 2017b) and EEA (2017).

Figure 22. EV sales (left axis) and market share (right axis), along with the ratio of battery EV (BEV) to plug-in hybrid EV (PHEV) sales in selected countries 2010-2016 (IEA, 2017a)

4.1.2 The European Union

The societal institutions surrounding transportation in the EU differ tremendously from those in the US, as do the barriers to sustainable personal transport and the policy approaches for attaining that goal. As with the US, the picture begins with historical culture and with governmental institutions. The two most obvious factors affecting European transport habits are the smaller land area of the countries and the lack of domestic oil reserves. The 28 countries of the EU combine to form a 4,479,968 sq km land mass, roughly half the size of the US (9,147,593 sq km), but boast a population of about 515 million people, almost 60% more than US inhabitants (CIA, 2017a, 2017b). The higher population density is tied to the fact that there are more urban areas on the continent spaced much less sparsely, and suburban life is much less celebrated. With the centuries-old history of European civilization, local economies have been well developed and institutionalized, which meant that even people in smaller villages had less reason to travel significant distances. Though the Schengen Agreement has allowed freedom of movement across most EU member state (MS) borders since 1985, the continent was not on such good terms during the early decades of the automobile. Therefore, with citizens generally contained to their own countries and suffering the harsh economic and infrastructural impacts of war, demand for personal vehicles would never reach the heights observed in America.

In 2012, there were 589.4 vehicles per 1,000 people in Western Europe, about 27% fewer than the US in 2012 or about as many as Americans owned in 1973 (see Figure 18) (EERE, 2014). Passenger vehicles accounted for 80.1% of land travel in terms of passenger-kilometers (pkm) within the EU in 2014, a rate about 21% greater than in 1995 and 9.4% more than 2000, but it was still 10.2% less than the 90.3% in the car-addicted US (Eurostat, 2016). This means Europeans are still riding the bus (8.8%), the train (7.2%) and the metro (1.7%), but are relying on cars more often for longer trips. Another category included for the EU but not for the US is 'powered two-wheelers' (P2W), at 2.14%, which points to the social acceptance of scooters in urban European environments. Similarly, bicycles are a large part of the culture of several European countries, and their cities are built to accommodate cyclists, who are not included in the 'land transport' statistics. Moreover, many urban areas in the EU are more 'walkable' than in the US in terms of size, layout, traffic, pollution and general comfort due to architecture. It is also very significant that these cities, as they are so old, were not built around cars or even horse carriages like many American cities. They can be very inaccessible to automobiles, and small cars are preferable simply for their maneuverability down narrow streets, let alone their fuel efficiency.

Even so, road transport (including commercial freight transport) accounted for 72.8% of CO_2 emissions in the sector (see Figure 23), and both passenger and freight transport activity are projected to maintain the steady increase in activity that has been observed since 1995 (see

Figure 24) (Vis, 2016). This activity amounted to approximately 278 million tonnes of oil equivalent (mtoe) or 85.12 billion gallons of road transport fuel (gasoline and diesel)[10] consumed in 2015 (see Figure 25) (Eurostat, 2017). This translates to 233.2 million gallons per day[11] and 165.3 gallons per capita per year, almost 70% less than the 566 gallons of gasoline and diesel consumed per capita per year in the US. This statistic is rather incredible considering that Americans only traveled by passenger car about 25% more than Europeans - 6 trillion pkm to about 4.77 trillion pkm in 2014 (Eurostat, 2016). As a measure of overall fuel efficiency per vehicle passenger, EU citizens traveled over 70% further per unit of gasoline than Americans, earning 56.1 pkm per gallon against 32.5 pkm per gallon, respectively.

The most obvious explanation for this is that European cars achieve better gas mileage, but as can be seen in Figure 26, the industry average fuel economy in the EU in 2015 was ~48 miles per gallon (MPG) compared to ~32 MPG in the US, or about 50% more efficient. There is another 20% unaccounted for which can likely be attributed to behavior and culture. For one, there must be more frequent carpooling in the EU[12] than in the US, where 85.8% of people's commutes to work were by car in 2013 and only 10% of those trips were in cars of two or more people (BOTS, 2015). A somewhat trivial indication of the cultural acceptance of carpooling in the EU is the popularity of the long-distance car sharing service "Bla Bla Car," which has not penetrated the US market. Second, the fuel economy statistics are lab results, so real gas mileage is still driver-dependent. Manual transmission continues to be popular in Europe, and coincidentally it grants the driver more control over engine efficiency than the US-favored automatic transmission. Also, the automatic engine idle start-stop technology which was pioneered in Europe has had a major but largely immeasurable effect on fuel economy (Simanaitis, 2012). Energy conservation is a behavioral institution in the EU, and the automobile industry has capitalized on this market demand in spite of the oil industry's interests.

[10] A large proportion of cars in the EU are diesel-powered (53%), unlike in the US, so the straight gasoline figure cannot represent the personal transport consumption in the EU like it can in the US.
[11] US: 505.5 million gallons of gasoline plus diesel per day
[12] Carpooling statistics for the EU could not be found, which may in itself be an indicator of its normalness.

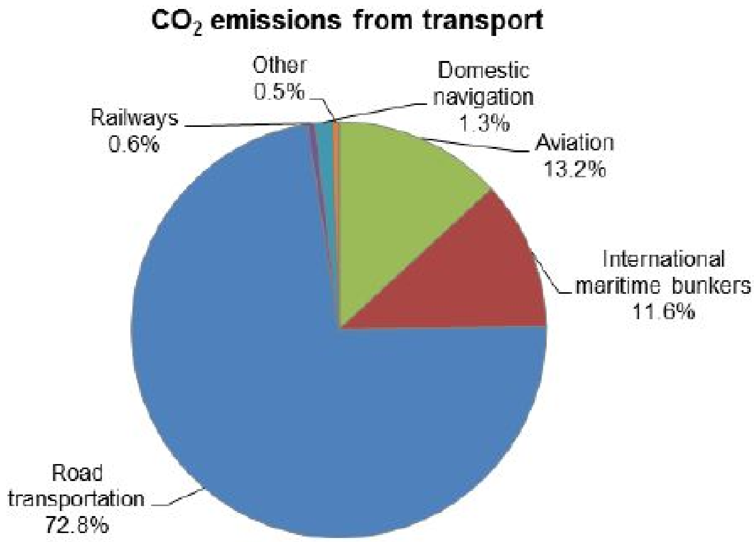


Figure 23. Relative shares of CO_2 emissions by mode of transport in the EU (Vis, 2016)

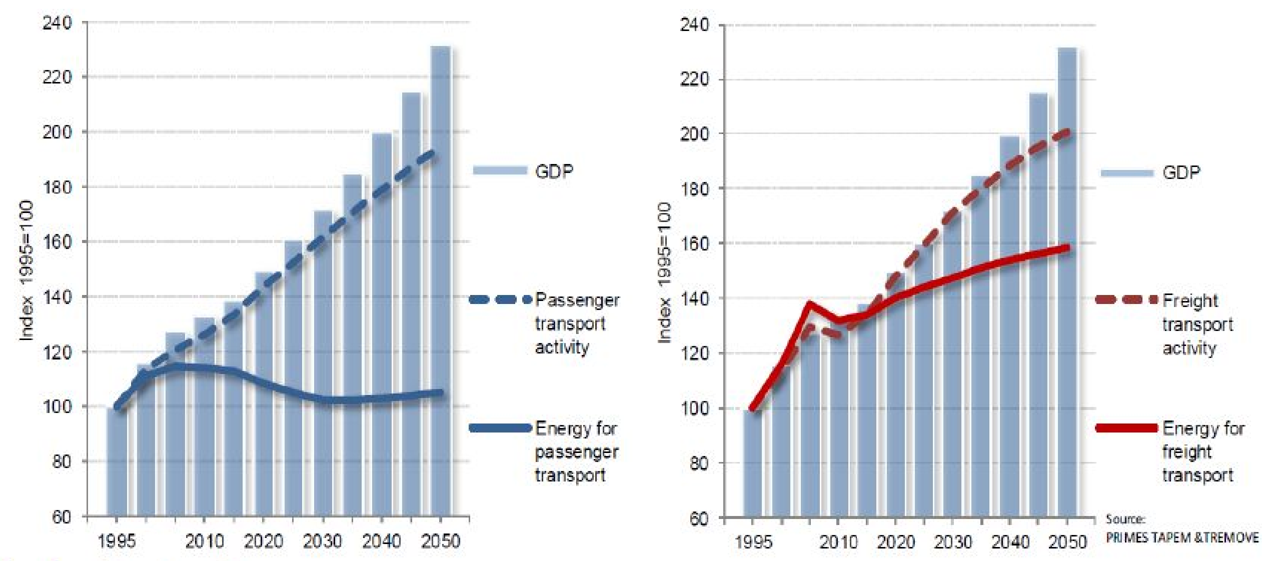


Figure 24. Recorded data of road transport activity from 1995-2015 and projections from the European Commission's Directorate-General of Mobility and Transport (DG MOVE) for activity until 2050 (Vis, 2016)

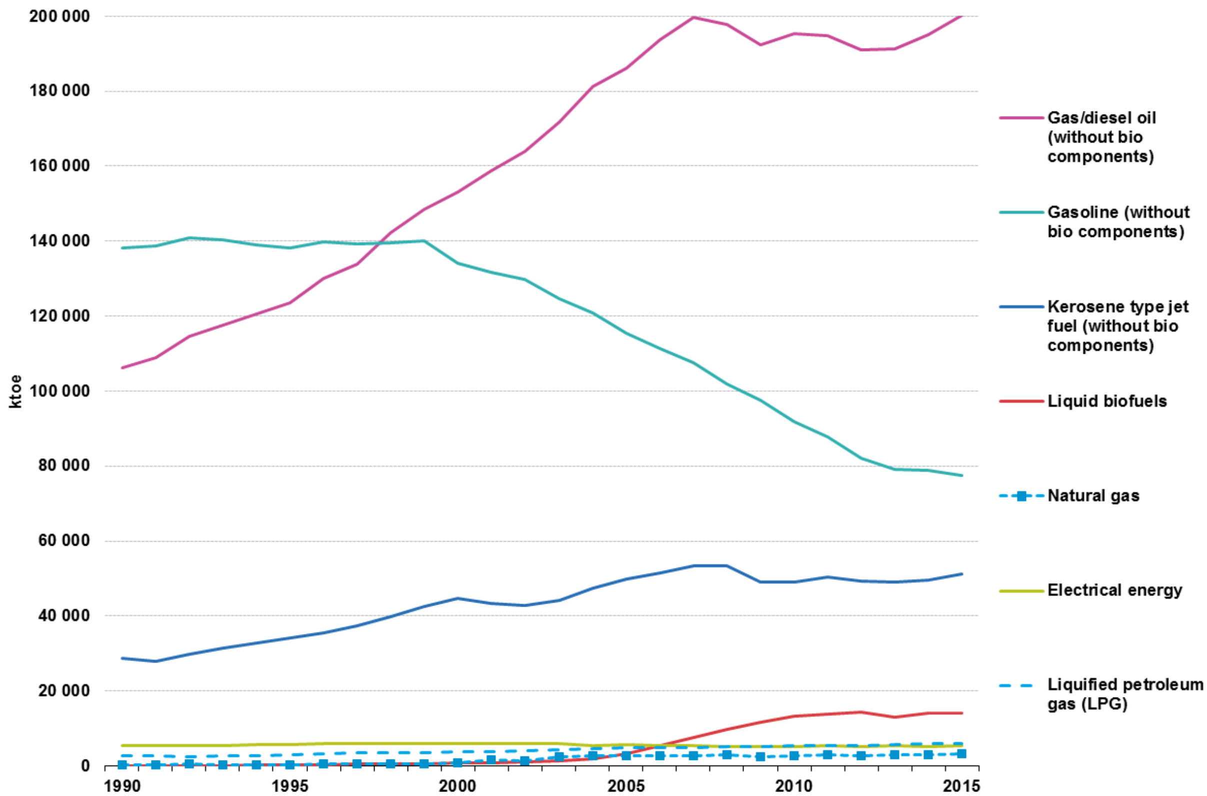


Figure 25. Final consumption by fuel type in the EU transport sector from 1990-2015 in kilotonnes of oil equivalent (ktoe) (Eurostat, 2017)

The nearly complete absence of petroleum beneath the continent has been a major driver of energy policy in European nations. The continent's historical sources of oil have been the politically unstable Middle East, its geopolitical nemesis Russia, and the US, its chief economic competitor[13]. The motivation to reduce oil dependency has therefore long been an institution of European governments for national security reasons. This is a likely explanation - along with the relatively sparse pollution levels - why the EU, not long after its formation, chose to adopt stricter standards than the US with respect to GHG emissions yet lagged behind in emission limits relating to air quality (Nesbit et al., 2016). In fact, leaded gasoline was not prohibited in the EU until 2000 when catalytic converters were finally required for new vehicles. This trend continues today, as diesel engines command a 53% market share in the EU and yet fewer restrictions are in effect for nitrous oxide (NOx) abatement technologies than in the US, where only 0.8% of cars are diesel (ibid.). On the other hand, diesel technology is now much more fuel efficient with lower carbon emissions than gasoline combustion.

[13] More recently, also Norway

The EU, from its leadership to its citizenry, has also exhibited a strong sensitivity to the international effort against climate change. In 1998, shortly following the Kyoto Protocol of 1997, the EU announced a voluntary agreement with the Association of European Automobile Manufacturers (ACEA) to set an emissions limit of 140 g/km (a 25% reduction) on all vehicles by 2008 (ibid.). Moreover, automakers were then required in 1999 to supply consumers with information about the CO_2 emissions from the car at the point of sale, explaining why Figure 25 shows gasoline consumption beginning to decline sharply in 1999 as well as the rise of diesel passenger cars. When the informal regulatory framework did not prove strong enough for compliance, the Commission set mandatory emissions standards in 2009 with Regulation (EC) 443/2009 (ibid.). This established ambitious targets for a fleet average of 130 g/km by 2015 and 95 g/km by 2021, and the European Parliament has indicated a target range of 68-78 g/km for 2025 (ibid.). These standards have led the EU to become a global leader in fuel economy with a vehicle average of 5.6 Lge/100km (IEA, 2017b); the ambition of EU emissions standards[14] in comparison to US fuel economy[15] is shown in Figure 26.

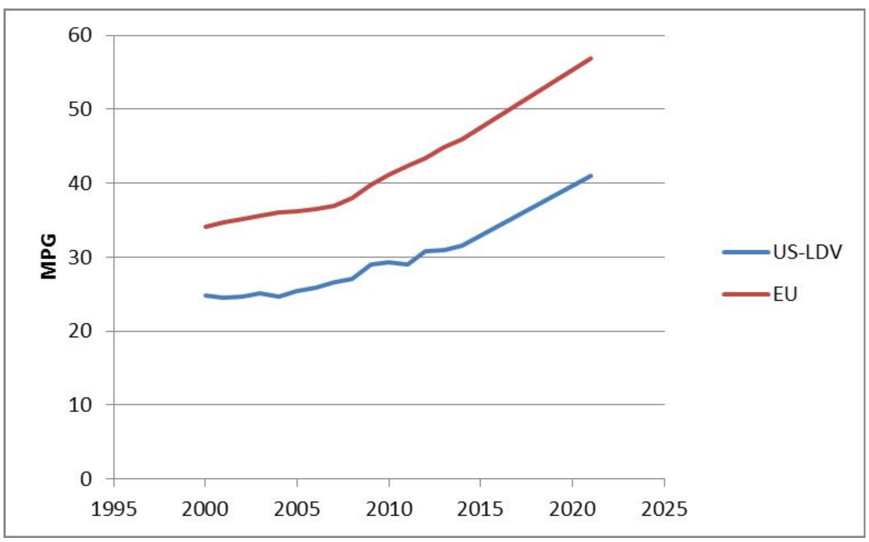


Figure 26. Comparison of historical fuel economy data and future emissions standards targets between the US and the EU in miles per gallon (MPG) (Nesbit et al., 2016)

[14] While the improvement rates are effectively parallel, fuel efficiency investments have been shown to suffer from diminishing returns, meaning the same relative improvements have come at much higher cost to automakers in the EU (IEA, 2017b).

[15] The US has regulated fuel economy since the 1975 corporate average fuel economy (CAFE) as part of the oil-shock-era energy security measures

There are, however, some criticisms to be made about the EU legislation. In fact, it can even be linked to the infamous "Dieselgate" scandal in which Volkswagen's TDI models were found to utilize "cheat device" software which produces reduced NOx emissions exclusively when subjected to emissions testing. While VW's action is indefensible, the business decision is understandable given the regulatory climate. The engineers found that their vehicles could not deliver the fuel efficiency required by the EU when using new NOx traps which would allow TDI engines to pass US emissions standards and thus enter the American market. VW would not have even had the chance to consider this offense against their customers and the planet if EU directives had not incentivized the rise of diesel. While EU legislators are certainly not to blame for the scandal, this should serve as a lesson that they should shift their focus on fuel efficiency to fuel transition. The long term goal is to eliminate our dependence on oil, so it would be wise to replace it as much as possible in the short term. Moreover, this route would be much more cost effective in both the short and long terms.

The technology to produce cars which accept pure ethanol and high-grade gasohol is readily available at marginal cost to the consumer, and they have been in mass production for decades in Brazil by the biggest car companies in the world (Joseph, 2013). In fact, almost every modern gasoline car contains software which can render it a flex fuel vehicle (FFV) fully capable of running on pure ethanol, and this after-market modification can be done without much expertise[16] (Dutreuil, Guerra, Grywalski, & Mehnert, 2008). However, the market penetration of diesel cars decreases the EU population's ability to exploit this and use ethanol. In other words, it severely limits the EU's absorptive capacity for alternatives, which is perhaps the most critical factor for breaking the TTIC lock-in, or any lock-in. A new technology cannot gain market share if the consumer base is incapable of using it. Diesel car owners are locked out from the ethanol market and the biofuels market in general as biodiesel is chemically different from diesel and requires a special engine. Renewable diesel will be an option in the future, but it is characterized by a less sustainable LCA than second generation ethanol.

The ideal vehicle fleet would empower drivers with the absorptive capacity and freedom to choose any transport fuel they prefer based on price, environmental responsibility and performance. PHEVs effectively package an ICE together with an EV, and they now outcompete

[16] There are also commercially available kits which allow car owners to easily adapt their car to be fuel flexible

‘conventional’ BEVs in many EU markets (see Figure 22). Like any other ICE, these can be easily modified to accept biofuel. Thus, a flex-fuel PHEV (FFPHEV) would not only prevent the lock-in of consumers to a single fuel choice but also the lock-out of either technology. That these have yet to enter the market is inexplicable, considering that the Chevrolet Volt was introduced in 2011 as an FFPHEV concept. It is now sold as a PHEV for just $100 less on the sticker price (Voelker, 2016), and it can be converted to an FFV in about 5 minutes with an aftermarket kit (Hall, 2015). Since there exist few, if any, techno-economic barriers, FFPHEV deployment should be an obvious policy objective in the EU, the US, and worldwide.

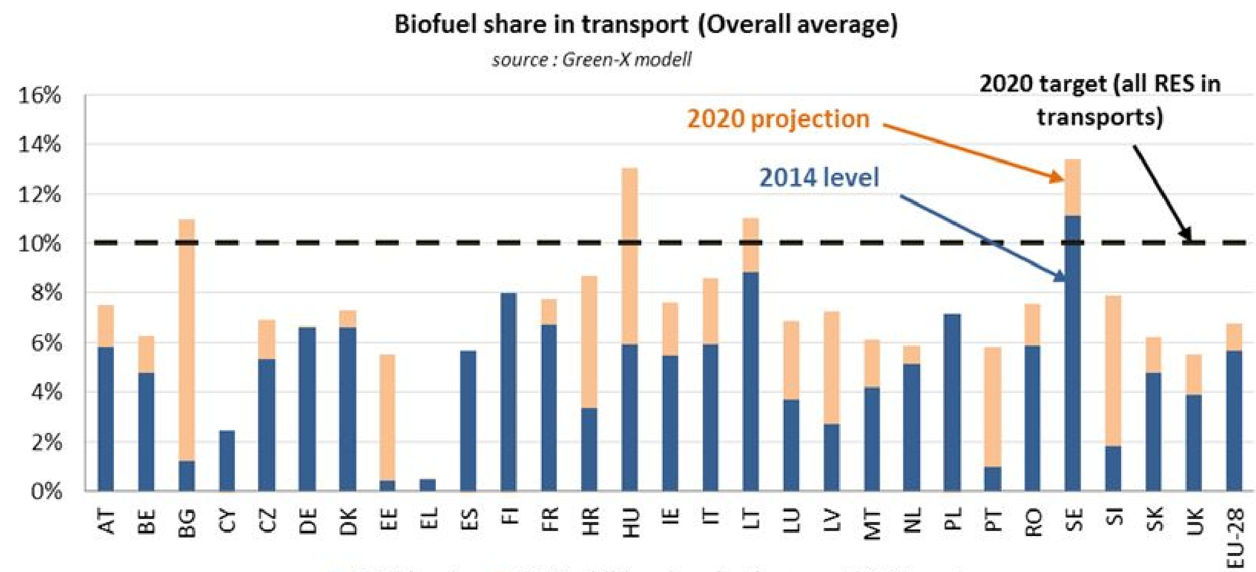


Figure 27. Share of biofuels in transport by MS in 2014 and projection for 2020 according to the EU Commission compared to the 2020 target for renewable energy in the sector (Vis, 2017)

Given how far ahead the EU has been in fuel conservation, it is quite surprising how far behind the Union remains in transport fuel transition. Biofuels accounted for only 5.75% of energy consumption in transportation (see Figure 27), while EV market share remains below 1% (see Figures 22 and 25). The slow progress in biofuels compared to the US is especially confounding considering how much more readily the continent embraced fuel ethanol a century ago. The return of ethanol interest was institutionalized by the Commission in 2003 with Directive 2003/30/EC, targeting a 5.75% share of renewables (RES) in transport by 2010. This was built upon in 2009 as part of the economy-wide Renewable Energy Directive (RED I)[17], setting a 2020 transportation target of 10% RES in each MS. Concurrently, the Fuel Quality Directive (FQD)[18] mandated a 6% reduction in the overall GHG intensity of transport fuels and also introduced sustainability criteria for biofuels. Specifically, a technology would only be counted toward the target if it saved at least 35% in GHG emissions compared to fossil fuels by measure of the "Well-to-wheels" Life Cycle Analysis (LCA) method. This criteria also accounted for emissions from direct land use change (LUC) at the recommendation of the IPCC and envisioned a progressive limit such that new biofuel installations in 2015 would have to prove a 50% GHG emissions cut[19].

However, in 2015 the FQD was updated to include another IPCC-identified phenomenon called indirect land use change (ILUC) in the assessment of biofuel technologies. Direct LUC[20] emissions or sinks refer to when new biomass production (e.g. agriculture or forestry) requires human-induced change of the land to be used. The most common causes are deforestation and grassland conversion for creating new farmland and the subsequent changes in soil carbon sequestration. While LUC normally carries a negative connotation, in some cases biofuel feedstocks can generate a relative carbon sink depending on where cultivated. ILUC, on the other hand, can only increase atmospheric carbon release. It describes the downstream effect of using arable land which could potentially produce food for energy purposes instead, resulting in the future need to cultivate additional land to feed a growing population. This theoretically anticipated cropland may then result in significant LUC emissions, and it may be displaced to regions of the world outside the EU which have less stringent policies against negative LUC impacts. Thus, even biomass production which has an immediate positive LUC effect can result in overall negative impacts for the climate due to long-term ILUC.

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[17] Directive 2009/28/EC

[18] Directive 2009/30/EC

[19] For comparison, the US currently enforces a 20% GHG reduction for conventional biofuels and a 50% reduction for advanced biofuels

[20] The IPCC always combines LUC with land use and forestry (LULUCF), whereas the EU substitutes LUC for the same concept

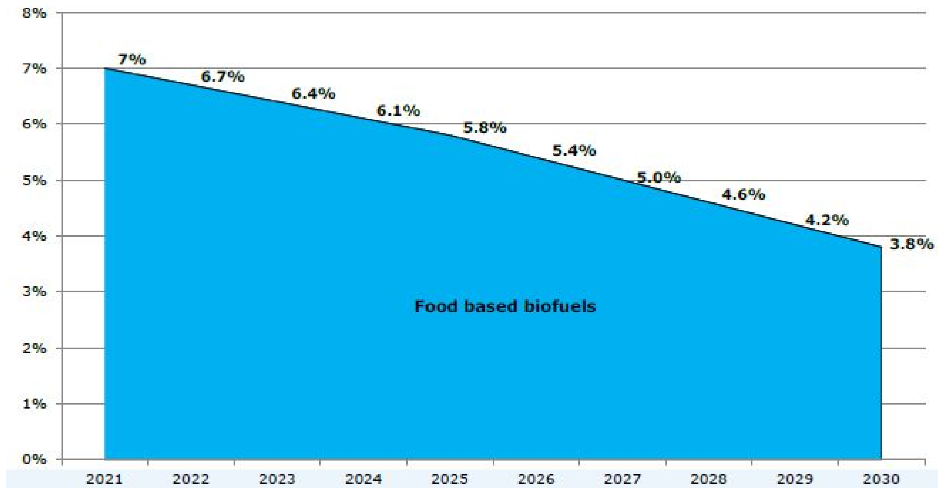


Figure 28. Gradual phase out of first generation biofuels down to pre-2008 levels by 2030 proposed by the EU in the RED II in response to ILUC (Vis, 2017)

ILUC is a very young field of study, and while it is thought to be highly consequential, its impacts cannot be reliably measured yet (and perhaps ever). The resultant GHG emissions can only be roughly estimated through modeling, and since the effects are expected to arise at some undetermined point in the future at an unspecified location, there is no way to test the validity of the modeling techniques. Analysts have therefore struggled to incorporate it into LCA calculations, and the EU mitigation policy relies on qualitative categorization. The FQD associates advanced biofuel feedstocks from wastes and algae with a “low risk” of ILUC as they do not compete directly for agricultural land, and purports conventional food-based biofuels to have a high potential for ILUC (European Commission, 2015). Second-generation non-food cellulosic crops such as miscanthus and switchgrass are also encouraged for deployment if they do not displace agricultural land (ibid.). The concern and uncertainty surrounding ILUC led the Commission to increase the stringency on new biofuels to be at least 60% GHG-saving, and the 2016 proposed amendment to the RED (RED II) would increase it again to 70% starting in 2021 (European Commission, 2016a, 2016b). Moreover, the FQD update in 2015 imposed a 7% cap on conventional biofuels by 2020, and the RED II will begin a phase out of food-based biofuels down to 3.8% in 2030 (see Figure 28).

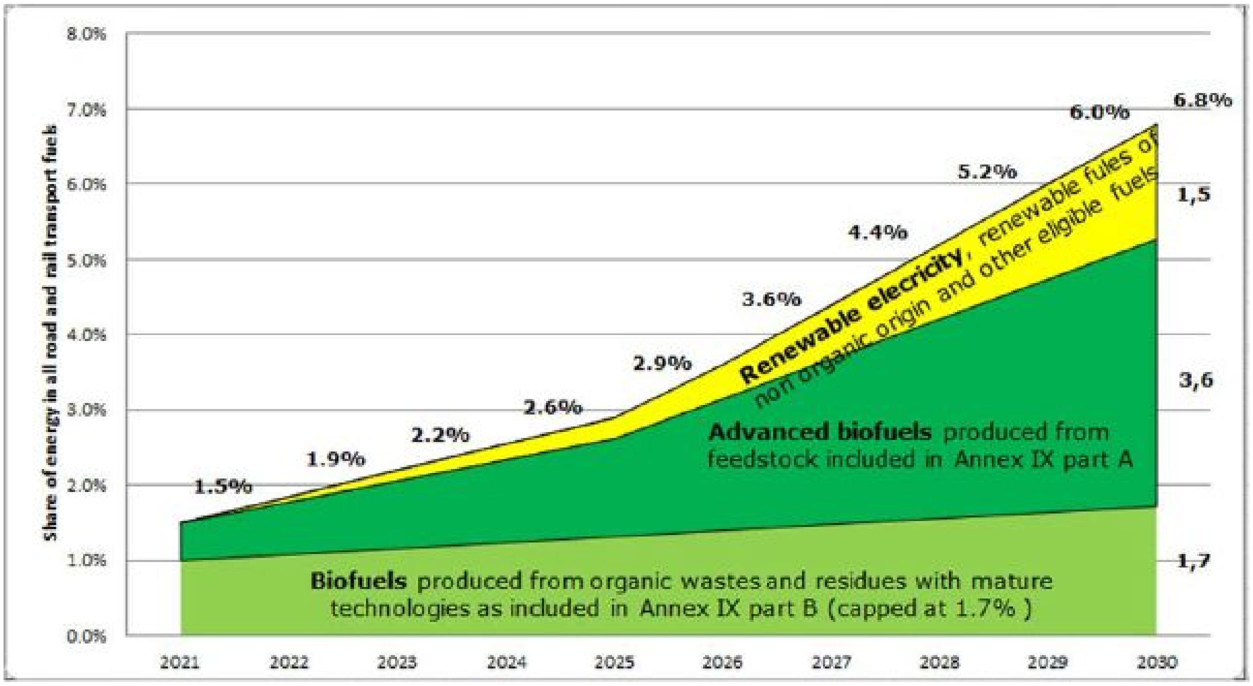


Figure 29. Projected growth of advanced biofuels and electricity (EVs, hydrogen fuel cells, etc.) from 2021-2030 by the European Commission in 2017 (Vis, 2017)

The EU has taken painstaking efforts to research the holistic impacts of its legislative decisions regarding the future of transport. In an email exchange with a European Commission adviser on decarbonisation of transport at the Directorate-General for Mobility & Transport (DG MOVE), the author asked about the EU's primary motivations for phasing out food-based crops. He responded, "The primary concern in capping 1st gen. food & feed –based biofuels were that they conflict with food & feed production, in particular through indirect land use change effects. One can question the extent to which EU policy has adverse impacts on food & feed prices, but the uncertainties and "unintended effects" cause policy makers (including European Parliamentarians) to refrain from promoting things of which they're not absolutely sure are of net benefit… EU policy now wants to concentrate its support on areas where there is no concern for unintended consequences: hence its emphasis on advanced biofuels" (see Appendix I). This portrays an admirable approach from EU lawmakers, demonstrating a devotion to true sustainability rather than surface-level aesthetic policymaking. However, Figure 29 depicts the projected impact of the current policies on advanced biofuel growth until 2030, and it is less impressive. In 13 years time, the advanced biofuels they are emphasizing are expected to remain less prevalent than the conventional biofuels being phased out, and total biofuel market share will be a meager 9.1%[21].

In response to a question regarding the new RED II proposal to require 70% GHG savings from biofuels, the DG MOVE adviser offered: “Yes, this is a very high bar. In effect, as you imply, there’s a trade-off between quantity and “quality” (i.e. in terms of sustainability) of sustainable biofuels. These thresholds take account of technical progress over time. But it’s also the prerogative of policy-makers to condition support. That the conditions are set high is a reflection of the wish for policy support to be concentrated on the best performing technologies… on what is unequivocally sustainable” (see Appendix I). The intentions of the EU lawmakers are noble, but they are not immune from influence. He continued, “When policy-makers are criticised for allowing low-sustainable biofuels to be promoted, etc. it’s normal that, at the next opportunity they try harder to avoid favouring things that are more controversial but concentrate support on what is unequivocally sustainable” (ibid.). The criticism referenced here is the public outcry against food-based ethanol upon learning about the potentially negated environmental benefits due to LUC and ILUC as well as its possible impact on future food supply and prices. This is a heated topic popularly referred to as the ‘food vs. fuel’ debate, and it has begun to shroud biofuels in a negative connotation in European society.

In the US, this debate is frequently fueled by the oil industry in their “public awareness” and lobbying efforts. In the EU, however, lobbying is generally a different institution than in the US. Though private interest representation is actually a compulsory input for policy making in the European Commission, a formal set of rules for lobbying practices are established in the Treaty of the EU. These encourage and enforce transparent, triangular dialogue between the governing bodies, representative associations and civil society. While there is direct evidence of Shell making an “influential lobbying effort in Europe… to remove binding renewable energy and energy efficiency targets from the EU’s climate change agenda” (InfluenceMap, 2016), the limited pull of oil companies in the EU is evidenced by the low rate of subsidization for petroleum and fossil fuel in general. The IMF estimates that EU-wide fossil fuel subsidies in 2011 amounted to USD 99 billion (see Figure 30), and that “the EU also has lower tax subsidies than the rest of the world” (Bárány and Grigonytė, 2015). Oil received about $10 billion in subsidies, representing only 4% of the amount granted by the US government.

[21] Not including electricity

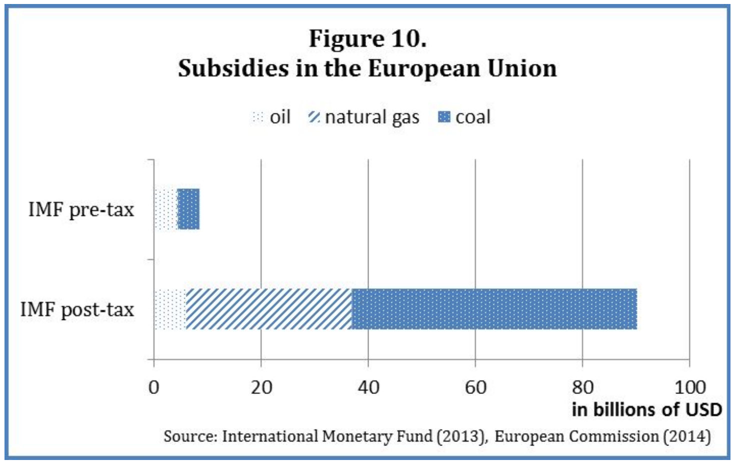


Figure 30. IMF estimates of the subsidies granted to the fossil fuels industry by the EU in 2011, both pre-tax and post-tax (Bárány and Grigonytė, 2015)

It is thus fair to assess that the EU is not subject at this point to the intentional lock-out forces that have so dominated the American political economy for decades. Instead, the EU governance is beholden to the interests of civil society and of its member states. This is a constant balancing act to consider and converge the ideas of such a diverse constituency, so in the realm of technology the lawmaking process often wisely defers to the power of science through the work of the Commission. In addition, it appears that the EU leadership is keenly aware of path dependency theory's widespread implications and is taking extreme caution not to lock in a potentially unsustainable TIC. Gregory Unruh, the founder of the carbon lock-in and TIC concepts, has previously proposed an interdependent policy suite comprised of six key components: 1) generating technological diversity through technology-specific support for emerging options and technology-neutral support for market-ready alternatives, 2) supporting new entrants and generating actors' diversity, 3) promoting learning-by-doing and learning-by-using, 4) promoting networking and learning-by-interacting, 5) fostering shared visions, and 6) improving the absorptive capacity and innovative-generative capacities in firms and countries (del Rio & Unruh, 2012). The EU seems to be closely following his model.

Directive (EU) 2015/1513 "called on the Commission to present without delay a comprehensive proposal for a cost effective and technology-neutral post-2020 policy in order to create a long-term perspective for investment in sustainable biofuels with a low risk of causing indirect land-use change and in other means of decarbonising the transport sector" (European Commission, 2016). The EU has also promoted technology-specific support and 'learning-by-using' for emerging technologies by funding large demonstration projects such as the €20.5 million provided to three algae biofuel pilot plants collectively referred to as the "Algae Cluster"[22] (Kenny et al., 2016)). Algae biofuels are a particularly intriguing technology because of microalgae's rapid growth rate, high CO_2 sequestration rate, ability to grow on otherwise useless land using treated wastewater or saltwater, and its ability to produce almost any fuel from ethanol to gasoline to natural gas. However, the only project of the three to report sustainability results to date calculated a much higher LCA than anticipated (Bradley, 2016), and it remains to be seen how much continued support will be received from the EU as algae biofuels continue down the learning curve.

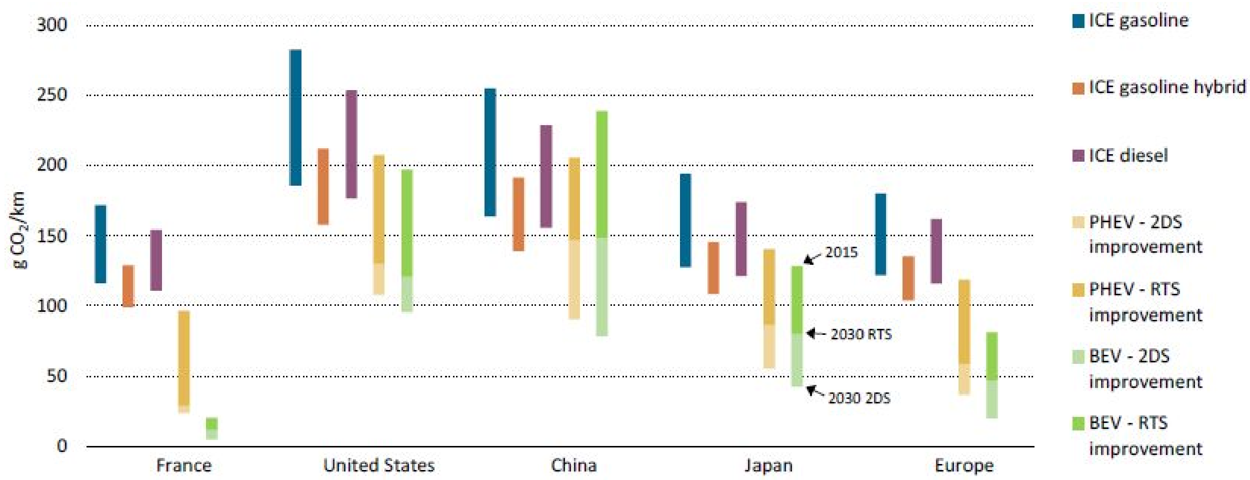


Figure 31. GHG emissions estimates for battery EVs (BEVs) and plug-in hybrids (PHEVs) compared to different ICE cars in select countries, with projections for 2030 corresponding to energy system carbon intensity based on the COP21 2DS and on the Reference Technology Scenario (RTS), reflecting current policies and targets (IEA, 2017)

In the DG MOVE adviser's own words, the EU has taken on "a 'learning-by-doing' approach to policy making" (see Appendix I). It has avoided lock-in from previous policy decisions as clearly demonstrated by its shifting targets for first generation biofuels, but this may result in some unintended consequences of its own. It has provided anything but a "long-term perspective for investment" and may put the whole biofuels sector at risk of losing the trust of investors. In other words, this technocratic adaptive approach may not be compatible with modern economic institutions and can potentially lead to financial lock-out. In fact, several

[22] Part of the Seventh Framework Programme (FP7) for research, technological development and demonstration (RD&D)

major EU countries have recently introduced and passed[23] legislation to ban all sales of petrol and diesel vehicles in the coming decades, perhaps motivated by the clear signal this offers investors. While this is a very positive development for a sustainable automotive future and would bring the world closer to the projected EV stock necessary to reach the 2DS (see Figure 32), the true performance will vary by country depending on its power generation mix. Based on the current decarbonization trajectory in the EU, an EV would produce ~50 gCO_2/km in 2030 (see Figure 31), compared to the 2025 proposal of 68 gCO_2/km for ICEs.

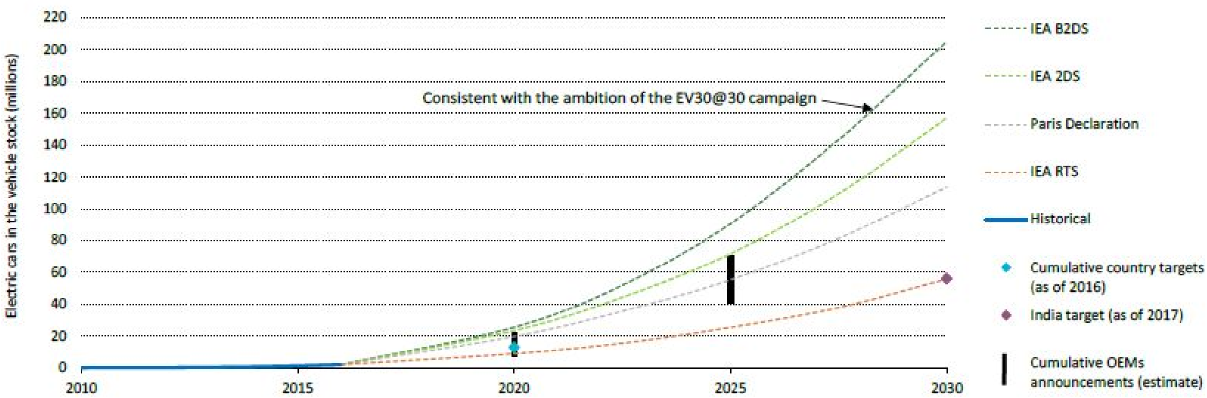
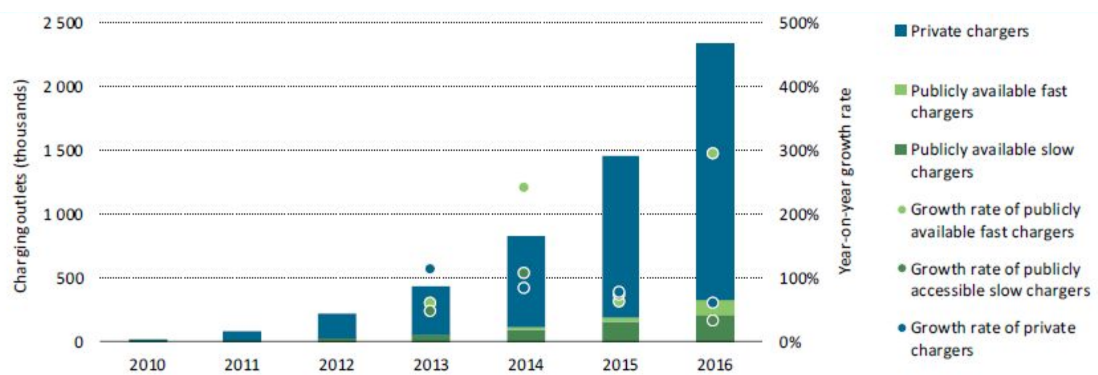


Figure 32. Deployment scenarios for electric cars until 2030 based on required decarbonization to meet COP21-related targets (RTS = reference technology scenario) (IEA, 2017)

Even so, an ICE ban may ultimately prove environmentally detrimental as it would inherently lock out biofuels, which are better equipped to displace oil in the short term and may even become the more sustainable option in the long term as advanced biofuels continue to develop. Figure 33 shows the current number of EV chargers worldwide, and while public fast chargers increased at a 300% rate in 2016, there are still under 200,000 stations the world around and the majority of them are in China (IEA, 2017). Charging infrastructure is a risky short-term investment because the returns are expected in the medium and long term, but technological progress could render today's chargers obsolete by then[24]. On the other hand, ethanol blending could be increased to 15% in the short term without incurring any infrastructural costs. Corrosion becomes a concern for higher ethanol content, primarily of natural rubber and certain metal parts

[23] Thus far, France and England are the only countries to officially pass legislation, implementing bans from 2050 and 2040, respectively. Norway was the first country in the world to introduce the ban, set for 2030. At least Germany and the Netherlands have also proposed the motion.
[24] Consider cell phone charging technology, which has improved in both speed and

(Price and Brokesh, N.D.; Joseph, 2013). However, synthetic rubber is actually more common nowadays, and gasket and hose replacement is simple and cheap. Metal gas tanks can be spray-coated with alcohol-friendly liners or replaced with plastic tanks at similar cost and ease (Price and Brokesh, N.D.). Carmakers could conceivably begin to produce FFVs exclusively at little to no increase in operational costs (ibid.). Existing gasoline pipelines would also need to be rendered corrosion-resistant through passivation, and new pipelines should use low-carbon steel, non-metals or ceramics (Singh, 2009). These represent marginal medium-term costs compared to developing a comprehensive EV charging network which may soon become a lock-out force against more optimal technologies.



Note: Private chargers in this figure are estimated assuming that each electric car is coupled with a private charger.

Figure 33. The growth of EV charging infrastructure from 2010-2016 (IEA, 2017)

Chapter 5. Conclusion and Policy Implications

If path dependency can teach us anything about the future of technology development, it is that the short term matters more than any medium or long term visions. This is particularly true in the face of climate change with the atmospheric CO_2 level exceeding 400 ppm for the first time in centuries and quickly approaching the 450 ppm target instituted by the IPCC, above which the carbon cycle begins an unpredictable positive feedback spiral. Coincidentally, we also find ourselves at a critical juncture on the path to sustainable transport in both the US and the EU. Both governments have placed a cap on the use of well-established conventional biofuels, and the other alternatives on the market (advanced biofuels and EVs) have not yet begun to exhibit increasing returns. The road ahead will depend on coordination between actors in the industries themselves, in supporting industries such as the automobile industry in particular, in government, and in society. This collective action must aim to construct an institutional environment in which these technologies can attain the critical mass to capture increasing returns to scale, by learning effects, through network effects and from adaptive expectations.

Moreover, the days of Ethyl Corp and shared leaded gasoline revenue for petroleum and automotive titans are over, and the TTIC is not as cohesive as it once was in both the EU and the US. The car industry has no natural dependency on the oil industry, and it has started to behave in this manner over recent years. This changing institutional arrangement provides the perfect environment for the alternative technologies to begin constructing their own TICs because there is an opportunity to coordinate efforts with the automotive industry, which has well-established institutional and political power in both societies. Support from the large car firms via increased output of EVs, PHEVs, FFVs and FFPHEVs would allow biofuels and EVs to capture increasing returns to scale, network effects and adaptive expectations. It should be in the automaker's best interest, as it was a century ago, to prepare for a post-oil world. Increased competition from new firms such as Tesla should provide extra motivation, but policy initiatives may be necessary to catalyze this industry shift. The US and the EU should envision a sustainable future of personal transport in which an EV TIC and a diversified biofuels TIC coexist, and in which the individual consumer has equal access to each. The governing bodies can foster this vision by providing regulatory and financial support for continued innovation in both fields along with the development of supporting infrastructure.

The regulatory objectives should begin with manufacturer tax incentives or outright mandates on the production of FFPHEVs. This market-ready technology unlocks the greatest potential for optimal sustainability in the transport sector and offers consumers freedom of choice in the fuels market, thus mitigating the risk of yet another techno-institutional lock-in. Many large car manufacturers regularly produce both FFVs and PHEVs, so the cost of RD&D is minimal for such a powerful, future-proof tool. FFPHEVs are also a more attractive investment for carmakers than 'revolutionary' technologies such as BEVs or hydrogen vehicles since they do not require any new infrastructure to perform, and thus short term returns in today's oil-dominant transport fuels market are not sacrificed. The price point in comparison to the low-end petrol car market remains the biggest question and potential hurdle to FFPHEV adoption, so this is where legislation will be necessary to artificially deflate costs through tax incentives. The US already implemented such a program for qualified BEVs and PHEVs (EERE, 2017), so this would simply have to be extended by the tax authorities, the Internal Revenue Service (IRS), to cover FFPHEV models. Production costs can be expected to decrease with further battery R&D as well as efficiency improvements in the supply chain and manufacturing process, so the subsidy can be gradually phased out accordingly.

Moreover, the US Senate proposed a mandate on the production of FFVs in 2006, called the Open Fuel Standard Act, but it has still yet to pass due to lobbying from the oil industry. This bill should be modified in favor of FFPHEVs, lest a new bill be introduced, but a clear objective for the alternative fuels sector should be to ramp up its lobbying budget. A partnership with the auto industry, a political stalwart in both the US and the EU, would be instrumental in this effort. Generally speaking, the climate action lobby needs to bolster its influence, as the total spending in 2015 was estimated to be under $5 million globally (InfluenceMap, 2016). In the US, at least, political contributions need to be considered as critical an investment as RD&D financing for portfolios directed toward sustainability and energy transition. Like a highway network, these political inroads essentially establish an infrastructure upon which new policies can drive new technologies. As the opposition lobby can attest, the returns on investment can be very lucrative. The primary focus of these funds should be to finance campaigns for new green-minded political candidates to facilitate a turnover of the incumbents captured by oil interests.

Meanwhile, the FQD in the EU has already led car manufacturers to invest heavily on innovation, forcing them to begin breaking away from their core rigidities. While this has started the EU automobile sector down what appears to be a suboptimal diesel-fueled path, continued fuel efficiency investments are subject to decreasing returns. Therefore, a transition to FFPHEV production may yet be the more cost effective route in the short term. FFPHEVs are certainly the more profitable long-term investment since this technology will be subject to increasing returns by network economies with both the biofuels market and EV charging infrastructure. FFPHEV legislation may be subject to some controversy in the EU because the shift from diesel to petrol and ethanol would require a slight rollback of the stringent EU fuel efficiency standards. This should be overshadowed, however, by the impact that this increased absorptive capacity will have on the European Energy Union, which lists consumer empowerment and future-proof infrastructure as two of its stated goals (European Commission, 2017). EU-wide adoption of FFPHEVs will open the door for diversely-sourced ethanol to be traded on energy exchanges, further strengthening the economy, the energy union, and the EU's energy security.

Financial support from both governments should entail continued technology-specific RD&D projects to improve LCA and techno-economic performance of advanced biofuels. Thus far, both the US and the EU have done well to identify promising feedstock candidates which minimize LUC and maximize GHG savings, including some crops such as miscanthus which reduce emissions by up to 115% (Wang, Han, Dunn, Cai, & Elgowainy, 2012) and waste streams from agriculture, forestry, paper mills and municipalities which have net positive LUC impact. Financial instruments for advanced biofuels once they are market-ready can take the form of technology-neutral subsidization for all biofuels above some threshold of GHG reduction, which would then let market forces select winners, or graded subsidies that favor the most sustainable feedstocks which prove a sufficient economic viability.

As for conventional biofuels, there are some emerging avenues to explore which could mitigate both LUC and ILUC. Advanced agricultural techniques such as intercropping and agroforestry have been shown to improve soil carbon sequestration and more consistent yields, and perennial corn crops significantly increase yield, soil carbon and are more cost effective in the long term (Kline et al., 2016). As for ILUC, a recent study pioneered the practice of ‘payments for ecosystem services’ (PES) which sent a mission to offer payments to forest owners in Uganda if they agreed not disallow deforestation for agriculture or biomass use. This resulted in GHG savings equal in value to 2.4 times the program cost (Jayachandran et al., 2017), and these missions could theoretically offer payments for afforestation or socio-technical programs to institute advanced agricultural techniques for even greater positive LUC effects. For the EU, this could be a worthwhile government program to indirectly offset ILUC, and it could be targeted to regions known for producing the crops being displaced in the EU by energy feedstocks. These options require further research, as ILUC does, but ideally the EU could reconsider the conventional ethanol phase out because the most critical short term goals are to phase out oil and to institutionalize biofuels which can later be more stringently regulated.

Finally, both governments should invest in fast-charging EV stations through auction systems for firms willing to install them regionally. As with any unestablished technology, the perception of risk is accentuated, but the optimizing agents surrounding EVs right now are primed for positive feedback if the charging infrastructure gap can be plugged. The inherent financial lock-out can be readily addressed by fiscal policy which mitigates the risk on private parties. Similarly, the inherent curriculum lock-out can be combatted through publicly-funded training programs and government-assisted development of new fields of study at higher education institutes. Technology-specific research grants and scholarships can also be legislated to motivate the younger generation to pursue these new careers. Together, these actions can build institutional forces into the market that can simultaneously break the inherent infrastructural lock-out which has prevented electricity from entering the transportation sphere.

Intentional lock-out, on the other hand, is more difficult to address through legislative action because many of its effects are manifested in the government itself. The current US leadership is so deeply captured by the oil lobby that the Department of Energy, the Environmental Protection Agency and the US Department of Agriculture have all been banned from disseminating any information on climate change (Lartey, 2017; Milman, 2017; Wolff, 2017). Together with the Department of Transportation, these are the exact governmental branches responsible for promoting and sponsoring transportation decarbonization, so in many ways intentional lock-out of sustainable alternative transport is as strong as ever in the US. There is hope for the continued increase of advanced biofuels production and blending mandates which were instituted a decade ago, but the funding for the other short term goals concerning EVs and FFPHEVs will likely have to rely on coordinated action in the private sector. The most critical actors will be the large automakers, who will hopefully realize the need to compete in EV technologies with Tesla's entrance into the middle class market. Not to be overlooked is the power of marketing, and some examples of selling points which may resonate with the American public are the high-octane performance of ethanol, the freedom of fuel choice that FFPHEVs offer, and the low cost of refueling EVs.

The EU, meanwhile, has already instituted fiscal resources specifically devoted to low-emission transport. The Connecting Europe Facility has allotted an annual budget of €24 billion, and the European Structural & Investment Funds reserves €39 billion each year for transport decarbonization (Vis, 2016). Together, these amount to over six times the annual oil subsidy, so they should be sufficient to have a market impact in the short term and medium term if the European Energy Union can adopt a coherent, common strategy. These goals are also explicitly supported by the European Fund for Strategic Investments (Juncker Plan) (ibid.), but these finance mechanisms must be coordinated to prevent excessive investment spikes into singular technologies. Given the broad horizon of sustainable transportation technology ahead (hydrogen fuel cells, biogas, synthetic gas, etc.), the medium term priority should be to support technological diversity in RD&D to determine the sustainability and feasibility of all potential fuels. Research towards a more precise definition of sustainability must also continue in parallel, particularly on ILUC and the relationships between biofuels and food supply and demand. The EU's long term objective, then, rather than its immediate goal, should be the Commission's stated desire for 'unequivocal sustainability' in personal transport, in which only the most proven technologies will receive public support. Too much specificity in the short term can only lead down the familiar path of lock-out and technological inertia. While the early history of motorized vehicles was largely a tale of luck, greed and lies in America, the EU has the opportunity to direct the future of sustainable transport through science, cooperation and transparency.

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Appendix I

Transcript of interview with [redacted], Adviser at the European Commission for DG Transport and Mobility, via email exchange, between 5 August 2017 and 7 August 2017:

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Dear [Redacted],

Please accept my warm regards in this unsolicited message. I was pointed in your direction by Gaspard Demur from DG Energy.

I am a Master's student of Global Energy Transition and Governance at CIFE (Centre International de Formation Europeene), a Commission-funded school headquartered in Nice. Mr. Demur was a guest lecturer for my program.

I am writing my master's thesis on the various barriers facing advanced biofuels and a robust bioeconomy in both the EU and the US, and I am currently reviewing the EU's biofuel policies. I've just had a look through two of your powerpoint presentations, which I appreciated for the graphics and the conciseness. I'm hoping you could take a few minutes to answer a few questions regarding the rationale behind the some of the new policies.

1. Could you please provide some insight as to the primary concerns driving the planned phase out of food crop-based biofuels? Would you say the top reason is the impact on future food supply, the insufficient GHG reductions, mounting ILUC emissions, or is it more an effort to create market share for advanced biofuels?

2. What potential consequences will there be for any Member States who do not abide by 2020 target of 10% biofuels in final transport energy consumption, and for the new 2020 and 2030 limits on food-based biofuels?

3. I also noticed in your graph titled "Promoting Innovation in Transport" that feedstocks listed *in Annex IX Part B (i.e. used cooking oil and some animal fats) are capped at 1.7%. I haven't seen mention of this cap in the RED 2015 update or anywhere else. Could you please explain this limit?*

4. The new criteria that new biofuels installations must save at least 60% in emissions compared to fossil fuels is commendable for ambition, but might it result in a further delay in commercialization of some advanced biofuels?

I would greatly appreciate any feedback you could provide me on these topics

Thank you for you time,
Stephen Bi

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Dear Stephen,

The people who you really need to speak to are in DG Energy, and they're in charge of the RED II proposal.
My answers are personal and shared with you for your academic work. I keep private my personal opinion on what the Commission has done, but defend the Commission's proposals.

1. The primary concern in capping 1st gen. food & feed –based biofuels were that they conflict with food & feed production, in particular through indirect land use change effects.
One can question the extent to which EU policy has adverse impacts on food & feed prices, but the uncertainties and "unintended effects" cause policy makers (including European Parliamentarians) to refrain from promoting things of which they're not absolutely sure are of net benefit.
What is being provided by the RED II Directive (as also RED I) is policy support for things.

Most energy, and most other economic production, has no support but has to stand on its own feet in the market economy. Food & feed-based biofuels will continue to be legal, and will be produced, but they just won't have the benefit of the same level of public policy support as they have enjoyed in the recent past. EU policy now wants to concentrate its support on areas where there no concern for unintended consequences: hence its emphasis on advanced biofuels from feedstocks listed in Annex IX. Creating market share for advanced biofuels has unqualified political support across the board.
I wouldn't say "insufficient GHG reductions" is a reason for the EU's policy. It is known that the high thresholds ensure net GHG added-value.

2. Legal consequences of not respecting 2020 targets are that the Commission will start legal proceedings against Member States (possibly before 2020 if it's clear that a MS is going to miss its target). Basically the normal rules for infringements apply. The European Court of Justice can ultimately apply sanctions, including financial sanctions on Member States. Sometimes, though, when EU policy has changed (or is about to change), infringement proceedings are withheld. I do not know what the Commission will be doing in this particular case.

3. The cap of 1.7% comes from Article 25 (1) (b) of the Commission proposal of 30/11/2016 RED II.

4. The 60% GHG saving threshold for new installations applies as a result of the 2015 ILUC amendment to RED I. The Commission even proposes in RED II a threshold of 70% GHG saving from 2021. Yes, this is a very high bar. In effect, as you imply, there's a trade-off between quantity and "quality" (i.e. in terms of sustainability) of sustainable biofuels. These thresholds take account of technical progress over time. But it's the also prerogative of policy-makers to condition support. That the conditions are set high is a reflection of the wish for policy support to be concentrated on the best performing technologies. Those who complain at this approach must understand that support isn't "owed" to anyone or anything. Conditions are always applied to support. That the conditions be stringent is normal in a world where its meaningless to support everything… Selectivity means more targeted support, which – it is

hoped – will be more effective and less criticized for having unintended consequences. When policy-makers are criticised for allowing low-sustainable biofuels to be promoted, etc. it’s normal that, at the next opportunity they try harder to avoid favouring things that are more controversial but concentrate support on what is unequivocally sustainable. Food-based ethanol producers are upset with the declining cap on food-based biofuels and are critical of the Commission. However, the Commission is acting rationally in saying it wants to avoid controversy and criticism and reserve support for advanced biofuels that are consensually supported. Ultimately, ethanol producers just haven’t made a convincing enough case with all stakeholders (such as Environmental NGOs). That’s hardly the fault of the Commission or European Parliament.

I hope this feedback is of use to you. You might also like to download a book I contributed to on climate policies. It’s available for free from the Commission’s website in EN, FR & Chinese.
https://ec.europa.eu/clima/sites/clima/files/eu_climate_policy_explained_en.pdf
https://ec.europa.eu/clima/sites/clima/files/eu_climate_policy_explained_fr.pdf
https://ec.europa.eu/clima/sites/clima/files/eu_climate_policy_explained_zh.pdf
It tells the story of EU climate-policy making, which you’ll see is not all-knowing, but rather takes a “learning-by-doing” approach to policy making. Biofuels are only touched on, and the book is a couple of years old, but you see how policy-making progresses incrementally, and how policy objectives may evolve over time in the light of experience and scientific knowledge.

Kind regards,

[Redacted]

Appendix II

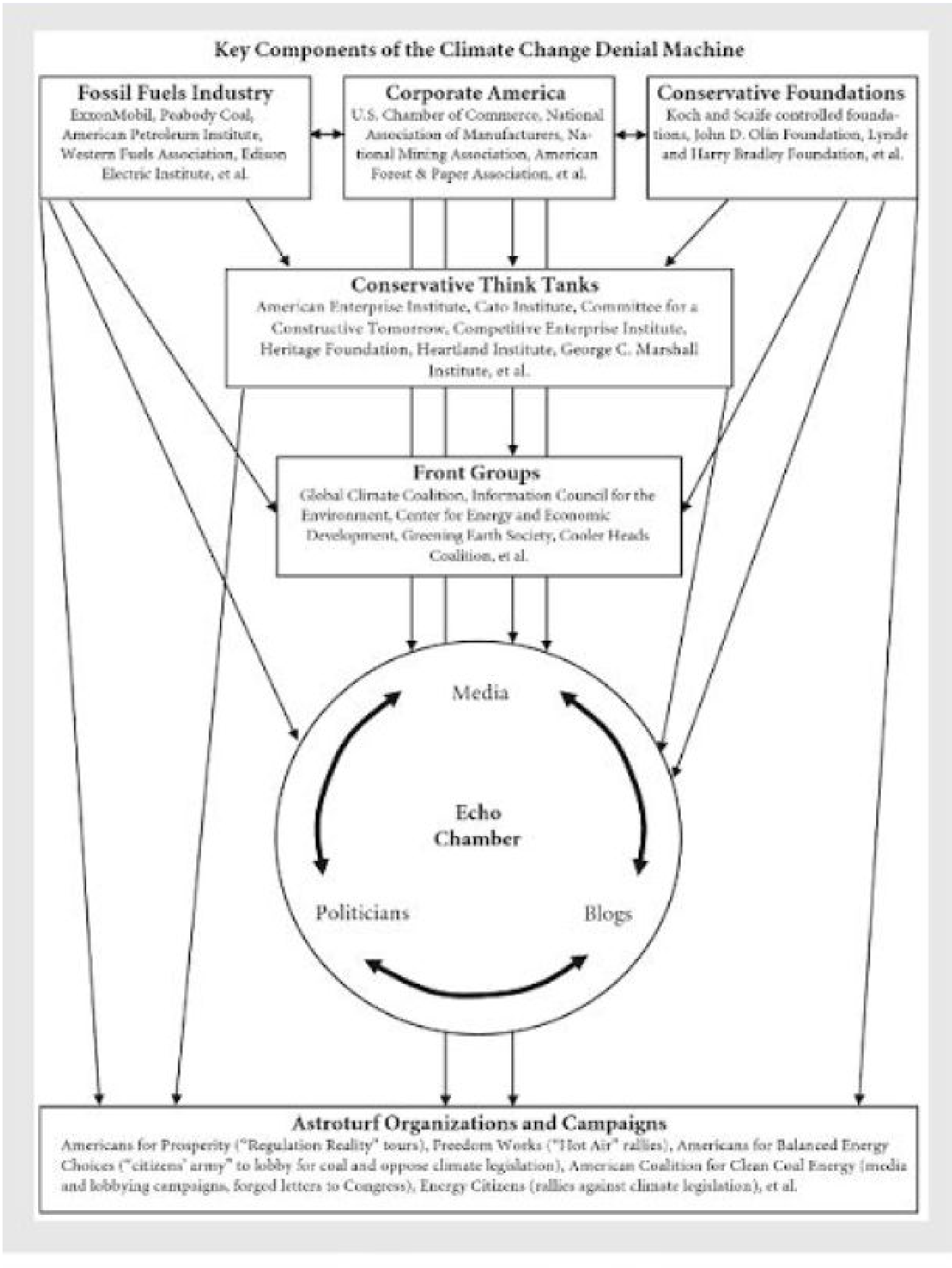

Figure 1. An illustration of the groups implicated in the climate change denial machine (Dunlap 2011)