Regulatory hold-up in the European car industry

A dynamic game of regulatory commitment and investment incentives

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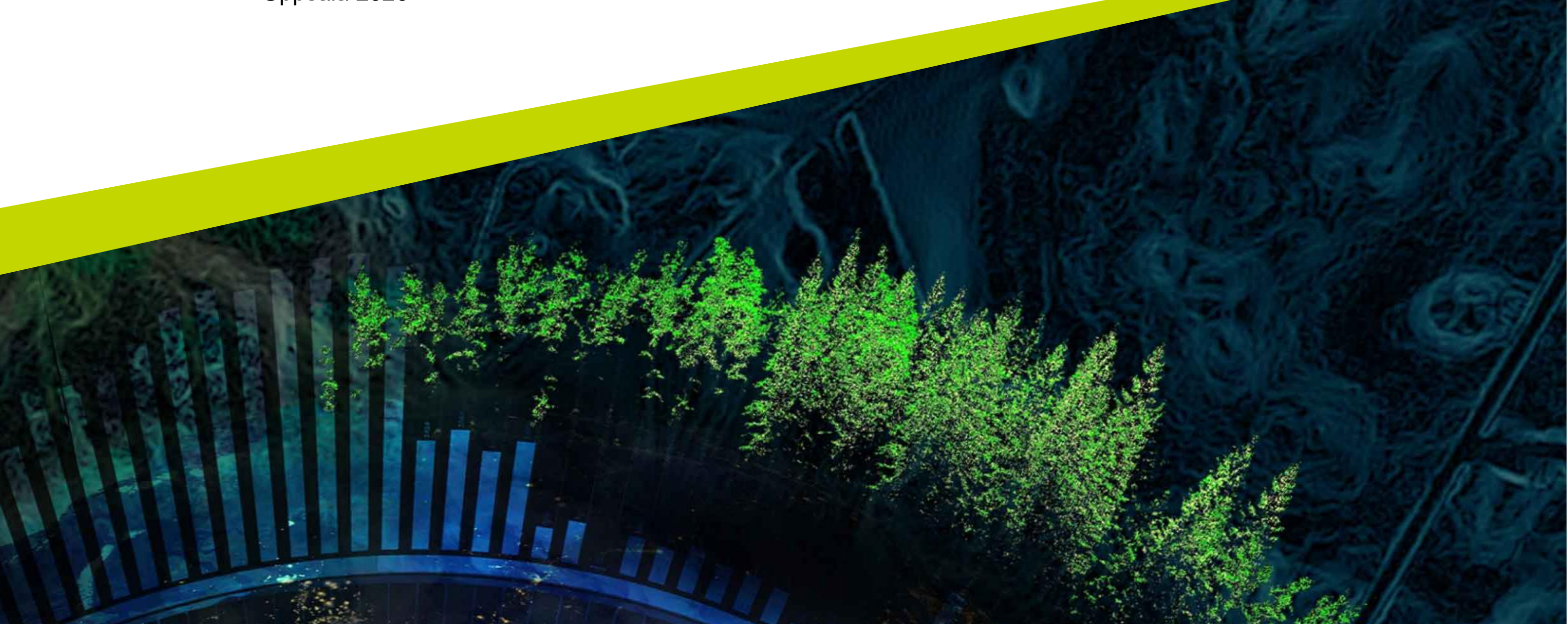

Regulatory hold-up in the European car industry. A dynamic game of regulatory commitment and investment incentives.

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Abstract

Environmental regulations are intended to encourage firms to invest in cleaner technologies and support the transition to a low-carbon economy. However, such investments are often costly and irreversible, making firms dependent on credible long-term policy commitments. Recent developments in the European automobile industry have raised questions about how policy credibility affects firms' investment incentives. This thesis examines how environmental regulation and regulatory credibility influence irreversible technology investment in the European automobile industry. A stylized dynamic game is developed in which a regulator interacts with two automobile manufacturers that differ in their technological comparative advantages. The analysis compares investment outcomes under laissez-faire conditions and under a CAFE-style regulatory regime. The results show that environmental regulation can redirect investment incentives toward battery electric vehicle (BEV) technology. Under laissez-faire conditions, firms invest according to their technological comparative advantages, whereas CAFE-style regulation induces both firms to adopt BEV investment. However, the results also indicate that the costs of regulation are distributed unevenly across firms, creating incentives for some firms to oppose stricter environmental policies despite complying with them once implemented. The findings suggest that the effectiveness of environmental regulation depends not only on policy design but also on policy credibility. If firms expect future regulations to be weakened or postponed, incentives to undertake irreversible investments may be reduced.

Keywords: Environmental regulation, policy credibility, irreversible investment, regulatory hold-up, battery electric vehicles, automobile industry.

Sammanfattning

Miljöregleringar syftar till att uppmuntra företag att investera i renare teknologier och stödja omställningen till en koldioxidsnål ekonomi. Sådana investeringar är emellertid ofta kostsamma och irreversibla, vilket gör företag beroende av trovärdiga och långsiktiga politiska åtaganden. Den senaste utvecklingen inom den europeiska fordonsindustrin har väckt frågor om hur politisk trovärdighet påverkar företags investeringsincitament. Denna uppsats undersöker hur miljöreglering och politisk trovärdighet påverkar irreversibla teknologiinvesteringar inom den europeiska fordonsindustrin. För att analysera detta utvecklas ett stiliserat dynamiskt spel där en regulator interagerar med två fordonsproducenter som skiljer sig åt i sina teknologiska komparativa fördelar. Analysen jämför investeringsutfall under laissez-faire-förhållanden och under ett CAFE-liknande regleringssystem. Resultaten visar att miljöreglering kan styra om investeringsincitament mot batterielektrisk fordonsteknik (BEV). Under laissez-faire-förhållanden investerar företagen i enlighet med sina teknologiska komparativa fördelar, medan CAFE-liknande reglering leder till att båda företagen investerar i BEV-teknologi. Resultaten visar dock även att regleringens kostnader fördelas ojämnt mellan företagen, vilket skapar incitament för vissa aktörer att motsätta sig strängare miljöpolitik trots att de anpassar sig till regleringen när den väl genomförs. Studien indikerar att miljöregleringens effektivitet inte enbart beror på regleringens utformning utan även på dess trovärdighet. Om företag förväntar sig att framtida regleringar kommer att försvagas eller skjutas upp kan incitamenten att genomföra irreversibla investeringar minska.

Nyckelord: miljöreglering, politisk trovärdighet, irreversibla investeringar, regulatoriskt hold-up-problem, batterielektriska fordon, fordonsindustri.

Table of contents

List of tables

List of figures

Abbreviations

BEV	Battery Electric Vehicle
CAFE	Corporate Average Fuel Economy
DEU	German automobile manufacturer
EU	European Union
ICE	Internal Combustion Engine
SPE	Subgame Perfect Equilibrium
SWE	Swedish automobile manufacturer
US	United States

1. Introduction

Environmental regulation plays a central role in the transition towards a low-carbon economy by encouraging firms to invest in cleaner technologies. In many industries these investments are costly, long-term and largely irreversible, requiring firms to commit substantial resources before the future regulatory environment is fully known. Investment decisions therefore depend not only on current policy but also on expectations regarding future policy implementation. If firms expect environmental regulations to be weakened, delayed or inconsistently enforced, incentives to undertake irreversible investments may be reduced (Pindyck, 1991; Taschini, 2021; Thomas et al., 2022).

The European automobile industry provides a timely example of this challenge. In 2025, the European Commission postponed the implementation of fleet-emission standards announced in 2019, delaying compliance until 2027 following industry pressure (Council of the European Union, 2025; European Commission, n.d.; Fröberg, 2025). While intended to provide temporary flexibility without changing the overall targets, manufacturers that had already invested heavily in electrification argued that the decision weakened regulatory credibility and reduced incentives for further investment (Fröberg, 2025). These contrasting responses illustrate the challenge of designing environmental regulation that is both stringent enough to encourage technological transition and sufficiently credible to support irreversible investment.

This dilemma has long been recognised in economic research. A substantial literature examines how environmental regulation influences technological change, innovation and firms' adoption of cleaner technologies (Porter & van der Linde, 1995; Jaffe & Palmer, 1997; Lanoie et al., 2011). Within the automobile industry, studies show that fleet-emission standards influence manufacturers' technology choices, pricing strategies and product portfolios (Klier & Linn, 2012; Jenn et al., 2016; Reynaert, 2021). At the same time, research on regulatory commitment and time inconsistency demonstrates that investment decisions depend on governments' ability to credibly commit to future policy (Schelling, 1958; Kydland & Prescott, 1977). When investments are irreversible, policy credibility becomes particularly important because sunk costs cannot be recovered if regulatory conditions change (Pindyck, 1991). Gersbach and Glazer (1999) formalise this problem by showing how imperfect regulatory commitment may discourage firms from undertaking socially desirable investments in cleaner technologies.

Recent developments in the European automobile industry demonstrate the continued relevance of these theories. The purpose of this thesis is to examine how regulatory credibility affects firms' incentives to undertake irreversible investments in low-emission technologies under CAFE-style environmental regulation. To address this question, the thesis develops a stylized dynamic game in which a regulator interacts with two representative automobile manufacturers and compares investment decisions under a laissez-faire benchmark and a CAFE-style regulatory regime. Rather than developing a new theoretical framework or predicting future developments, the thesis applies established economic theories to analyse a contemporary policy problem through a dynamic game-theoretic framework. The thesis addresses the following research question:

How does regulatory credibility affect firms' incentives to undertake irreversible investments in low-emission technologies under CAFE-style environmental regulation?

The remainder of the thesis is organised as follows. Chapter 2 reviews the literature. Chapter 3 presents the methodological approach and develops the theoretical model. Chapter 4 presents the results. Chapter 5 discusses the findings in relation to the existing literature and considers their policy implications. Chapter 6 concludes.

2. Literature review

This chapter reviews the economic literature on environmental regulation, firms' investment incentives and regulatory commitment. It concludes by synthesising these perspectives to motivate the analytical framework developed in this thesis.

2.1 Environmental regulation and firms’ investment incentives

Environmental regulation is a central policy instrument for addressing pollution by internalising environmental costs that would otherwise not be reflected in market prices (OECD, n.d.). Carbon pricing illustrates this mechanism. Analysing the Swedish carbon tax, Andersson (2019) finds that it substantially reduced transport-sector carbon emissions while having only limited effects on economic growth.

Beyond correcting market failures, a substantial literature examines how environmental regulation influences firms' incentives to invest in cleaner technologies. The Porter Hypothesis argues that appropriately designed regulation may stimulate innovation rather than simply increase compliance costs (Porter & van der Linde, 1995). Although subsequent empirical research generally supports a positive relationship between regulation and innovation, evidence that innovation fully offsets compliance costs or improves productivity remains mixed.

Empirical studies further show that environmental policy influences firms' investment behaviour. Jaffe and Palmer (1997) find that stricter environmental regulation increases research and development expenditure, while Johnstone et al. (2010) show that renewable energy policies stimulate technological innovation by increasing patenting activity. Similarly, Lanoie et al. (2011) find that innovation may partially offset compliance costs over time, although these benefits depend on firms' ability to convert innovative activity into productivity gains. Together, these studies suggest that environmental regulation encourages investment in cleaner technologies, although its economic effects vary across institutional and industrial contexts.

The automobile industry provides a particularly relevant setting because environmental regulation has increasingly focused on promoting the transition to low-emission vehicles. Rather than prescribing specific technologies, Corporate Average Fuel Economy (CAFE) regulations establish fleet-emission targets while allowing manufacturers flexibility in how compliance is achieved (Karplus & Paltsev, 2012; Kiso, 2019).

Evidence from the automobile industry indicates that manufacturers respond strategically to these incentives. Fleet-emission standards influence technology choices, product characteristics and compliance strategies (Klier & Linn, 2012; Jenn et al., 2016; Reynaert, 2021). Moreover, Puller (2006) argues that firms may innovate not only to comply with existing regulation but also to influence future regulatory standards. Overall, the literature suggests that environmental regulation encourages technological innovation while firms' investment decisions depend on both current policy incentives and expectations regarding future regulation.

2.2 Regulatory commitment, policy credibility and irreversible investment

The literature reviewed in the previous section demonstrates that environmental regulation influences firms' incentives to invest in cleaner technologies. However, these incentives depend not only on the stringency of environmental policy but also on whether firms perceive announced regulations as credible over the lifetime of their investments. Because investments in low-emission technologies often involve substantial sunk costs and long planning horizons, firms must form expectations about future policy before committing resources.

This perspective is rooted in the literature on regulatory commitment and time inconsistency. Schelling (1958) argues that credible commitment is fundamental to strategic interactions because current decisions are influenced by beliefs about future behaviour. Extending this argument, Kydland and Prescott (1977) demonstrate that governments may face a time inconsistency problem: policies that appear optimal before private investment occurs may no longer be optimal once firms have committed resources. As circumstances change, policymakers may therefore revise previously announced policies, weakening the credibility of future commitments. Anticipating this possibility, firms incorporate expectations about future policy into current investment decisions.

Policy credibility becomes particularly important when investment is irreversible. Pindyck (1991) argues that uncertainty creates an option value of waiting because firms cannot recover sunk costs if market conditions or public policy change unexpectedly. Similarly, Taschini (2021) shows that uncertainty surrounding future environmental policy increases the value of flexibility, influencing firms' investment decisions under regulatory uncertainty. Together, these studies suggest that the effectiveness of environmental policy depends on both the incentives it creates and firms' confidence in future policy implementation.

The interaction between policy credibility and environmental regulation has received increasing attention in theoretical research. Gersbach and Glazer (1999) show that regulators may have incentives to relax environmental standards after firms have undertaken irreversible investments, causing firms to invest less than is socially desirable because they cannot rely on previously announced commitments. Similarly, Puller (2006) argues that firms may undertake strategic innovation to influence future regulatory standards rather than simply responding to existing regulation. Together, these studies show that firms' investment decisions reflect strategic interactions between regulators and firms, where expectations about future policy shape current investment behaviour.

Overall, the literature suggests that policy credibility complements environmental regulation. While environmental policy creates incentives for technological investment, these incentives may weaken when future policy is perceived as uncertain or subject to revision. Understanding firms' investment behaviour therefore requires considering both environmental regulation and the credibility of long-term policy commitments. Together, these perspectives provide the theoretical basis for the analytical framework developed in this thesis.

2.3 Literature synthesis and theoretical motivation

The literature reviewed in the previous sections provides complementary explanations of firms' investment behaviour under environmental regulation. While the environmental regulation literature shows that policy instruments influence firms' incentives to invest in cleaner technologies, the regulatory commitment literature emphasises that these incentives also depend on the credibility of future policy commitments. Because investments are often costly, long-term and irreversible, firms consider both current regulatory incentives and expectations regarding future policy implementation. Together, these perspectives suggest that firms' investment behaviour reflects the interaction between regulatory incentives, firms' expectations and governments' ability to maintain credible long-term policy commitments.

This synthesis provides the theoretical motivation for the analytical framework developed in this thesis. A dynamic game-theoretic framework is well suited to analysing how regulatory credibility influences firms' incentives to undertake irreversible investments under CAFE-style environmental regulation. Rather than developing a new theoretical perspective, the model applies established theories of environmental regulation, regulatory commitment and irreversible investment to examine a contemporary policy problem in the European automobile industry.

3. Method and data

This section develops the theoretical framework used to analyze how environmental regulation and imperfect policy commitment affect firms' technology investment decisions.

3.1 Methodological approach

This thesis adopts a theoretical modelling approach to analyse how regulatory credibility influences firms' incentives to undertake irreversible investments under CAFE-style environmental regulation. Rather than relying on econometric analysis or observational data, the study develops a stylized dynamic game that captures the strategic interaction between a regulator and automobile manufacturers.

A theoretical framework is appropriate because the research question concerns sequential decision-making under imperfect policy commitment. Firms must decide whether to undertake costly and irreversible investments before future policy implementation is fully known, while regulators may subsequently have incentives to revise previously announced policies. These forward-looking interactions are difficult to analyse using static analytical frameworks but can be examined explicitly within a dynamic game.

The model builds on the theoretical literature reviewed in Chapter 2, particularly the literature on regulatory commitment, time inconsistency and irreversible investment (Schelling, 1958; Kydland & Prescott, 1977; Pindyck, 1991; Gersbach & Glazer, 1999). It is intentionally stylized and is not intended to replicate the full complexity of the European automobile industry. Instead, the objective is to isolate the economic mechanisms through which regulatory credibility influences firms' technology investment decisions.

The analysis is conducted as a sequential game and solved using backward induction, with equilibrium defined as a Subgame Perfect Equilibrium (SPE). This solution concept ensures that firms' investment decisions and the regulator's policy choices are mutually consistent at every stage of the game, making it well suited to analysing commitment problems in environmental regulation.

3.1.1 Economic environment

The model represents a stylized European automobile market in which firms compete under either a laissez-faire regime or a CAFE-style environmental regulation. Rather than replicating the full complexity of the European automobile industry, the model isolates the key economic mechanisms through which regulatory credibility influences firms' technology investment decisions.

The model considers two markets, labelled Germany and Sweden. These labels do not represent the actual German and Swedish automobile markets but serve as simplified analytical environments for the two representative European producers. They are used to distinguish firms with different technological comparative advantages rather than to replicate country-specific market characteristics. For simplicity, the two markets are assumed to be identical in size, allowing equilibrium outcomes to be driven by technology choices, production costs, regulatory incentives and comparative advantages rather than differences in market size or demand conditions.

$Let\ national\ markets\ be\ indexed\ by\ m \in \{1,2\}, where$

$$m = \begin{cases} 1: German\ market \\ 2: Swedish\ market \end{cases}$$

The game consists of three strategic actors: a regulator representing the European Union, a German automobile manufacturer (DEU), and a Swedish automobile manufacturer (SWE). It also includes an exogenous, non-strategic Chinese battery electric vehicle (BEV) producer to capture the increasing competitive pressure from Chinese electric vehicle manufacturers and provide a more realistic competitive environment for European firms.

$Let\ manufacturing\ firms\ be\ indexed\ by\ i \in \{1,2,3\}, where$

$$i = \begin{cases} 1: DEU\ (German\ manufacturing\ firm) \\ 2: SWE\ (Swedish\ manufacturing\ firm) \\ 3: China\ (Chinese\ manufacturing\ firm) \end{cases}$$

The model includes two vehicle technologies: Technology A, representing internal combustion engine (ICE) vehicles, and Technology B, representing battery electric vehicles (BEVs). Both European firms are assumed to produce both technologies, reflecting the diversified product portfolios of contemporary automobile manufacturers. Firms are modelled as supplying both technologies rather than specialising in either ICE or BEVs.

$Let\ vehicle\ technologies\ be\ indexed\ by\ j \in \{A, B\}, where$

$$j = \begin{cases} A: ICE\ (Internal\ combustion\ engine\ vehicle) \\ B: BEV\ (Battery\ electric\ vehicle) \end{cases}$$

3.1.2 Consumers

Consumer demand is modelled using a Cobb–Douglas utility function because it provides a simple and tractable representation of consumer preferences while ensuring positive demand for all goods. Rather than reproducing the full complexity of automobile purchasing decisions, the model captures how relative prices and consumer preferences influence market demand. Consumers allocate expenditure across three vehicle categories: European ICE vehicles, European BEVs, and Chinese BEVs.

Let V_{miA} denote consumption of European ICE vehicles, V_{miB} consumption of European BEVs, and V_{m3B} consumption of Chinese BEVs. Consumer preferences are represented by the utility function

$$U_{mi}(V_{miA}, V_{miB}, V_{miB}) = V_{miA}^{1-\alpha_i-\beta_i} V_{miB}^{\alpha_i} V_{m3B}^{\beta_i},$$

where $(1 - \alpha_i - \beta_i)$, α_i and β_i are preference parameters satisfying $\alpha_i, \beta_i \in (0,1)$ and $1 - \alpha_i - \beta_i > 0$. The parameters α and β represent consumer preferences for European and Chinese BEVs respectively. Higher parameter values imply a larger share of expenditure allocated to the corresponding vehicle category.

Consumers are subject to a budget constraint given by

$$W_{mi} = P_{miA}V_{miA} + P_{miB}V_{miB} + P_{m3B}V_{m3B},$$

where P_{miA}, P_{miB} and P_{m3B} denote vehicle prices and W represents total consumer expenditure within the market.

Marshallian utility maximization yields the following demand functions:

Demand of European ICE vehicles:

$$V_{miA} = \frac{1 - \alpha_i - \beta_i}{P_{miA}} W_i,$$

Demand of European BEVs:

$$V_{miB} = \frac{\alpha_i}{P_{miB}} W_i,$$

Demand of Chinese BEVs:

$$V_{m3B} = \frac{\beta_i}{P_{m3B}} W_i.$$

The demand functions imply that demand increases with market size and consumer preferences but decreases with vehicle prices. Investment lowers production costs within the selected technology and, under perfect competition, translates directly into lower prices, increasing consumer demand and equilibrium sales. Firms' investment decisions therefore affect market outcomes through their impact on production costs, prices and demand. The Cobb–Douglas specification abstracts from many factors influencing automobile demand, including product quality, driving range, charging infrastructure and brand loyalty. This simplified structure isolates the relationship between environmental regulation, technology investment and market demand.

3.1.3 Firms

A key assumption of the model is that firms must decide where to direct technology investment before the future regulatory environment is fully known, making investment the link between environmental regulation, policy credibility and market outcomes. Let I_{ij} denote the investment decision of firm i in technology j, where $I_{ij} \in \{A, B\}$. Each firm chooses one technology in which to invest: $I_{ij} = I_{iA} + I_{iB} = 1$.

Investment is assumed to be technology-specific and irreversible. Once undertaken, it becomes a sunk cost and cannot be reallocated across technologies, capturing the central mechanism underlying the regulatory hold-up problem. Investment affects production costs through a technology-specific efficiency parameter. Let C_{ij} denote the baseline production cost of firm i in technology j and let δ_{ij}, where $0 < \delta_{ij} < 1$, represent the cost-reducing effect of investment. If firm i invest in technology j, production costs become $C_{ij}(I_{ij}) = \delta_{ij}\bar{C}_{ij}$. Otherwise, production costs remain at the baseline level: $C_{ij}(I_{ij}) = \bar{C}_{ij}$. Lower values of δ_{ij} imply greater efficiency improvements and larger cost reductions.

The model further assumes that firms differ in their technological comparative advantages. DEU has a comparative advantage in ICE technology, while SWE has a comparative advantage in BEV technology. These differences are captured through variations in baseline costs and investment efficiencies, implying that identical regulatory incentives may generate different investment responses.

Because firms maximise equilibrium sales, investment decisions depend on expected future market conditions and regulatory outcomes. Firms therefore face a strategic trade-off between the expected benefits of investment and the possibility that environmental regulation may later be weakened or postponed. This interaction between investment incentives and future regulatory behaviour constitutes the core mechanism analysed in this thesis.

Investment reduces production costs within the selected technology. Under perfect competition, lower production costs translate directly into lower prices, increasing consumer demand and equilibrium sales:

$$I_{ij} \rightarrow\downarrow C_{ij} \rightarrow\downarrow P_{mij} \rightarrow\uparrow V_{mij}.$$

3.1.4 Regulatory regimes

To examine how environmental policy influences technology investment and market outcomes, the model considers two alternative regulatory environments. Rather than evaluating a specific real-world policy, the comparison isolates how regulatory intervention affects firms' incentives to invest in competing technologies. The two regimes therefore provide a benchmark for analysing the effects of environmental regulation and regulatory credibility.

The first regime represents a weak-policy environment. No technology-specific taxes or subsidies are imposed on automobile production, such that $\tau = 0$ and $\sigma = 0$, where τ denotes the tax rate on ICE vehicles and σ the subsidy rate on BEVs. Without policy intervention, firms choose investment strategies based solely on consumer demand, production costs and technological comparative advantages. This laissez-faire equilibrium provides a benchmark for analysing investment decisions in the absence of environmental policy.

The second regime introduces a stylized CAFE-type environmental policy. Rather than replicating existing regulations, it captures the central economic mechanism underlying fleet-emission standards. The regulator imposes an ad valorem tax on ICE vehicles and an ad valorem subsidy on BEVs, such that:

$P_{miA} = P_{miA}\ (1+\tau) = C_{iA}(1+\tau)$ and $P_{miB} = P_{miB}\ (1-\sigma) = C_{iB}(1-\sigma)$,

where $P_{miA}\ (1+\tau)$ and $P_{miB}\ (1-\sigma)$ denote consumer prices after policy intervention and $C_{iA}(1+\tau)$ and $C_{iB}(1-\sigma)$ production costs.

By increasing the relative price of ICE vehicles and reducing that of BEVs, the regulator shifts consumer demand towards low-emission technologies, increasing the expected returns to investment in those technologies. The policy therefore affects firms both directly through relative prices and indirectly by altering future market opportunities.

The distinction between the two regimes is central to the commitment problem analysed in this thesis. If firms believe environmental regulation will be implemented as announced, investment in low-emission technologies becomes more attractive. However, if firms expect regulation to be weakened or postponed, expected investment returns decline. The effectiveness of the CAFE regime therefore depends not only on the announced policy but also on the credibility of its implementation.

Comparing the laissez-faire benchmark with the CAFE regime makes it possible to examine how environmental regulation affects technology investment, market outcomes and the strategic interaction between firms and policymakers. It also allows the analysis to assess whether imperfect policy credibility may undermine the investment incentives environmental regulation is intended to create.

3.2 Timing of the game

The model is structured as a sequential three-stage game between a regulator and two automobile manufacturers. Firms undertake irreversible investments before future policy outcomes are fully known, while policymakers may later have incentives to revise previously announced policies. This timing reflects the literature on regulatory hold-up and time inconsistency. Because investments become sunk costs once undertaken, firms base investment decisions not only on announced policy but also on expectations regarding whether future policy commitments will be maintained. The games three stages is summarized in Table 1.

Table 1: Timing of the game

Stage	Action
1	The regulator announces a policy target and firms choose technology investments
2	The regulator observes firms' investments decisions and may revise policy
3	Policy is implemented and market outcomes are realised

3.2.1 Stage 1: Policy announcement and investment decisions

In the first stage, the regulator announces an environmental policy target which could be either strict or weak. This announcement provides information regarding the future regulatory environment and influences firms' expectations about future market conditions. The regulator is assumed to implement a common policy across the entire model economy, implying that both firms face identical regulatory conditions.

$$Let\ initial\ announced\ policy\ be\ indexed\ by\ X \epsilon \{S, W\}, where$$
$$X = \begin{cases} S: Strict\ CAFE\ regulation \\ W: Weak\ CAFE\ regulation \end{cases}$$

Following the announcement, the two firms simultaneously choose their technology investment strategies. A key assumption of the model is that firms (i) produce both ICE and BEV vehicles but choose only one technology (j) in which to invest $(I_{ij} \in \{A, B\})$. Investment affects next stage market outcome and is calculated to reduce production costs. Production costs are determined by baseline technology costs and a cost-reducing investment factor. Let $\bar{C}_{ij}$ denote the baseline production cost form firm i and technology j and let $\delta_{ij} \epsilon (0,1)$ represent the technology specific investment efficiency parameter. If a firm invests in technology j, marginal production costs are reduced according to $C_{ij} = \bar{C}_{ij}\delta_{ij}$, where lower values of δ_{ij} imply greater cost reductions from investment. For the technology the firm chooses not to invest in, the production costs remain at the baseline level $\bar{C}_{ij}$. The parameter δ_{ij} therefore captures the effectiveness of investment in improving production efficiency across technologies and firms. Let production costs be determined by the following:

$$C_{ij}(I_{ij}) = \begin{cases} \bar{C}_{ij}, & if\ I_{ij} = 0\ (no\ investment) \\ \delta_{ij}\bar{C}_{ij}, & if\ I_{ij} = 1\ (investment) \end{cases} \qquad with\ 0 < \delta_{ij} < 1.$$

Because investments are assumed to be irreversible, firms cannot subsequently recover these expenditures or redirect investment once the decision has been made. Taken together, these assumptions create a simplified but analytically tractable environment in which the relationship between environmental regulation, policy credibility and irreversible investment can be examined in a transparent manner. At this stage, firms must form expectations regarding future policy implementation. Their investment decisions therefore depend not only on current production costs and consumer demand, but also on beliefs regarding future regulatory behaviour.

3.2.2 Stage 2: Regulatory re-optimization

In the second stage, the regulator observes firms' investment decisions. By this stage, investment expenditures have already been incurred and therefore constitute sunk costs. Firms are effectively locked into their chosen investment strategies. The regulator is assumed to pursue a policy objective that balances environmental performance and economic outcomes. In stage 1, strict environmental regulation may be desirable because it encourages investment in cleaner technologies and supports long-term emission reductions. However, once firms have already invested and these investments have become sunk costs, the regulator may face different incentives. Policymakers may place greater weight on short-term considerations such as industrial competitiveness, employment and market activity. Consequently, a policy that appeared optimal ex ante may no longer be considered optimal ex post. This stage captures the commitment problem at the centre of the analysis. Because firms have already undertaken irreversible investments, the regulator may have incentives to weaken previously announced regulation without immediately affecting past investment decisions. The regulator therefore decides whether to maintain the originally announced policy or revise it.

$$Let\ revised\ policy\ announcement\ be\ indexed\ by\ X^* \epsilon \{S, W\}, where$$
$$X^* = \begin{cases} S\colon Strict\ CAFE\ regulation \\ W\colon Weak\ CAFE\ regulation \end{cases}$$

3.2.3 Stage 3: Policy implementation and market outcomes

In the final stage, the regulatory environment is implemented, and market outcomes are realised. Firms compete in the automobile market under the policy conditions determined in stage 2, and equilibrium prices, quantities and technology outcomes are established. If the implemented policy (X^*) differs from the policy initially announced (X), regulatory credibility is weakened.

Anticipating this possibility, firms may become less willing to undertake costly investments in low-emission technologies already in stage 1.

Because the model is solved using backward induction, the analysis begins with the market outcomes in stage 3, then examines the regulator’s incentives in stage 2, and finally determines firms’ optimal investment decisions in stage 1. This solution method allows firms’ expectations regarding future policy behaviour to be incorporated directly into current investment decisions.

The timing structure is therefore essential to the model. By separating policy announcement, investment and policy implementation into distinct stages, the framework captures how imperfect regulatory commitment may influence firms’ incentives to undertake irreversible investments and thereby affect the effectiveness of environmental regulation.

3.3 Equilibrium Concept

The model is analysed using game-theoretic methods. Because the interaction between firms and the regulator unfolds sequentially over time, the appropriate solution concept is Subgame Perfect Equilibrium (SPE). SPE requires that each player's strategy is optimal at every stage of the game and eliminates non-credible threats. This property makes it particularly suitable for analysing regulatory credibility and commitment problems.

The game is solved using backward induction. Backward induction is a solution method for sequential games in which the analysis begins in the final stage of the game and proceeds backwards to the initial decision stage. Firms therefore base their investment decisions not only on current market conditions, but also on expectations regarding future regulatory behaviour.

The solution proceeds from Stage 3 to Stage 1. First, market outcomes are determined given firms’ investment decisions and the regulatory environment. Second, the regulator’s incentives are analysed conditional on these market outcomes. Finally, firms choose investment strategies while anticipating both future market conditions and the regulator’s potential policy response.

The resulting equilibrium is a Subgame Perfect Equilibrium in which firms and the regulator behave optimally at every stage of the game. This framework allows policy credibility to influence investment decisions directly. If firms expect environmental regulation to be implemented as announced, investment in low-emission technologies becomes more attractive. Conversely, if firms anticipate that regulation may later be weakened or postponed, incentives to undertake irreversible investments may be reduced. The equilibrium concept therefore captures the central mechanism examined in this thesis: how imperfect regulatory commitment may affect technology investment under environmental regulation.

3.4 Calibration

The model is calibrated using stylized parameter values to illustrate the economic mechanisms under investigation rather than reproduce the exact characteristics of the European automobile industry. The calibration assumes that DEU has a comparative advantage in internal combustion engine (ICE) technology, while SWE has a comparative advantage in battery electric vehicle (BEV) technology. These differences are captured through variations in baseline production costs and investment efficiency parameters, resulting in different technology investment incentives. The labels DEU and SWE therefore represent firms with different technological positions rather than the actual German and Swedish automobile industries. For simplicity, the two markets are assumed to be identical in size, ensuring that equilibrium outcomes are driven by technological characteristics and regulatory incentives rather than market size. Table 2 presents the model parameters and their economic interpretation, including consumer preferences, market size, production costs, investment efficiency and environmental policy instruments.

Table 2: Baseline parameterization

Parameter	Economic significance	Type
$1 - \alpha_i - \beta_i$	ICE share/preference on home market	Demand parameter
α_i	BEV share/ preference on home market	Demand parameter
β_i	Chines BEV share/preference (competition)	Demand parameter
W_i	Market size/income	Exogenous variable
$\bar{C}_{iA}$	ICE baseline cost	Technology parameter
$\bar{C}_{iB}$	BEV baseline cost	Technology parameter
δ_{iA}	ICE investment efficiency	Investment parameter
δ_{iB}	BEV investment efficiency	Investment parameter

τ	ICE tax	Policy parameter
σ	BEV subsidy	Policy parameter

Table 3 reports the parameter values used under the laissez-faire benchmark. In this scenario, all policy instruments are set equal to zero, providing a reference point against which regulatory outcomes can be evaluated.

Table 3: Parameter values under Laissez-faire

Parameter	**DEU**	**SWE**
ICE share on home market/preference	$1-\alpha_1-\beta_1$	$1-\alpha_2-\beta_2$
BEV share on home market/preference	$\alpha_1 = 0.4$	$\alpha_2 = 0.4$
Chines BEV share/preference (competition)	$\beta_1 = 0.10$	$\beta_2 = 0.10$
W (market size/income)	$W_1 = 2$	$W_2 = 2$
ICE baseline cost	$\bar{C}_{11A} = 35$	$\bar{C}_{22A} = 40$
BEV baseline cost	$\bar{C}_{11B} = 60$	$\bar{C}_{22B} = 50$
ICE investment efficiency	$\delta_{11A} = 0.95$	$\delta_{22A} = 0.95$
BEV investment efficiency	$\delta_{11B} = 0.90$	$\delta_{22B} = 0.90$
Tax on ICE vehicles	$\tau = 0$	$\tau = 0$

Table 4 presents the parameter values used under the CAFE-regulation scenario. In this specification, an ICE tax is introduced to discourage investment in emission-intensive technologies. The model further includes a BEV subsidy, which is determined endogenously such that total tax revenues from ICE vehicles exactly finance total subsidy payments to BEV producers. The subsidy rate is therefore not imposed exogenously but is calculated as part of the equilibrium solution, ensuring that the regulator's budget remains balanced. The balanced-budget assumption is adopted to isolate the effects of environmental regulation and regulatory credibility without introducing government financing or fiscal policy considerations.

Table 4: Parameter values under CAFE regulation

Parameter	**DEU**	**SWE**
ICE share on home market/preference	$1-\alpha_1-\beta_1$	$1-\alpha_2-\beta_2$

BEV share on home market/preference	$\alpha_1 = 0.4$	$\alpha_2 = 0.4$
Chines BEV share/preference (competition)	$\beta_1 = 0.10$	$\beta_2 = 0.10$
W (market size/income)	$W = 2$	$W = 2$
ICE baseline cost	$\bar{C}_{1A} = 35$	$\bar{C}_{2A} = 40$
BEV baseline cost	$\bar{C}_{1B} = 60$	$\bar{C}_{2B} = 50$
ICE investment efficiency	$\delta_{1A} = 0.95$	$\delta_{2A} = 0.95$
BEV investment efficiency	$\delta_{1B} = 0.90$	$\delta_{2B} = 0.90$
Tax on ICE vehicles	$\tau = 0.2$	$\tau = 0.2$

The model was implemented and solved numerically in MATLAB. Separate programs were developed for the laissez-faire benchmark, the CAFE-regulation scenario and the strategic ICE–BEV scenario. For each scenario, the programs calculate equilibrium prices, demand, sales and regulatory budget outcomes based on the calibrated parameter values. Sensitivity analyses were conducted by varying one parameter at a time while holding all remaining parameters constant. Critical threshold values were identified numerically as the points at which firms switch between ICE and BEV investment.

The complete MATLAB programs are provided in the appendices. Appendix 1 contains the MATLAB code for the laissez-faire benchmark, Appendix 2 contains the code for the CAFE-regulation scenario, Appendix 3 contains the code for the strategic ICE–BEV scenario, and Appendix 4 contains the robustness and sensitivity analyses.

3.5 Simplifying assumptions

Like all economic models, the framework developed in this thesis relies on simplifying assumptions. These assumptions are introduced to keep the model analytically tractable and to isolate the relationship between environmental regulation, regulatory credibility and irreversible investment rather than to reproduce the full complexity of the European automobile industry.

A first simplifying assumption concerns market structure. The model assumes perfect competition, implying that firms are price takers and vehicle prices equal marginal production costs in equilibrium. Firms are therefore evaluated according to equilibrium sales rather than profits. Although the European automobile industry is characterised by imperfect competition, product differentiation and strategic pricing, adopting perfect competition allows the analysis to isolate the effects of technology investment and regulatory incentives without introducing additional strategic dimensions.

A second simplification concerns the representation of firms, technologies and markets. The model includes two representative European firms, denoted DEU and SWE, operating in two markets of equal size. These labels do not represent actual firms or national markets but distinguish firms with different technological comparative advantages. DEU is assumed to possess a comparative advantage in ICE technology, whereas SWE has a comparative advantage in BEV technology. The model further includes only two vehicle technologies, ICE vehicles and BEVs, where BEVs represent the low-emission technology targeted by environmental regulation.

Finally, investment is assumed to be technology-specific and irreversible. Once undertaken, investments become sunk costs and cannot be reallocated across technologies. Although firms may partially reverse investments or adapt production over time in practice, this assumption captures the central mechanism underlying the regulatory hold-up problem and allows the analysis to focus on how expectations regarding future policy influence current investment decisions.

4. Results

This chapter presents and interprets the equilibrium outcomes generated by the model. The analysis first compares investment incentives under laissez-faire conditions and under CAFE-style regulation. It then examines how the costs and benefits of regulation are distributed across firms and how these distributional effects may create incentives to oppose environmental policy. Finally, the robustness of the results is evaluated through a sensitivity analysis.

4.1 Model results

4.1.1 Laissez-faire Equilibrium

Table 5 presents the equilibrium outcomes under laissez-faire conditions, where firms make investment decisions solely based on market incentives, production costs and technological comparative advantages. The results show that Germany (DEU) achieves slightly higher equilibrium sales under ICE investment (0.04341) than under BEV investment (0.04339). Germany therefore chooses to invest in ICE technology. Sweden (SWE), by contrast, achieves higher sales under BEV investment (0.0428) than under ICE investment (0.0423) and consequently chooses to invest in BEV technology. The resulting equilibrium is characterised by technological specialization. Each firm invests in the technology in which it holds a comparative advantage: Germany specializes in ICE production, while Sweden specializes in BEV production. Total market sales amount to 0.0862.

Table 5: Laissez-faire equilibrium outcomes

Firm	**Sales under ICE investment**	**Sales under BEV investment**	**Optimal technology choice**	**Equilibrium sales**
Germany (DEU)	0.04341	0.04339	ICE	0.0434
Sweden (SWE)	0.0423	0.0428	BEV	0.0428
Total market	0.0857	0.0862	-	0.0862

Source: Author's calculations using MATLAB.

Although the difference between Germany’s ICE and BEV outcomes is relatively small, it is sufficient to make ICE investment the preferred strategy under laissez-faire conditions. This result illustrates that, in the absence of environmental regulation, firms invest according to their existing technological advantages rather than environmental objectives. Consequently, market incentives alone do not generate a complete transition towards low-emission technologies within the model. The laissez-faire equilibrium therefore serves as an important benchmark for evaluating the effects of environmental regulation. It establishes the investment pattern that emerges when firms respond solely to private economic incentives and provides a point of comparison for assessing whether policy intervention can alter technology investment decisions.

4.1.2 CAFE Equilibrium

Table 6 presents the equilibrium outcomes under CAFE regulation. The policy consists of an ICE tax $(\tau = 0.2)$ and a BEV subsidy (σ) where the subsidy is determined endogenously such that tax revenues from ICE vehicles finance BEV subsidies. The introduction of regulation changes firms' investment incentives by altering the relative attractiveness of ICE and BEV technologies. Both firms achieve higher equilibrium sales under BEV investment than under ICE investment. Germany (DEU), which invested in ICE technology under laissez-faire conditions, now switches to BEV investment. Sweden (SWE) continues to prefer BEV technology.

The resulting equilibrium is therefore characterized by a common BEV-BEV outcome. The policy alters the relative returns to investment to the extent that Germany's initial comparative advantage in ICE production is no longer sufficient to make ICE investment the preferred strategy. Environmental regulation therefore succeeds in redirecting investment incentives toward the low-emission technology. Total market sales decline slightly from 0.0862 under laissez-faire conditions to 0.084026 under CAFE regulation. While the policy succeeds in promoting BEV investment, the reduction in aggregate sales suggests that the transition towards cleaner technologies may involve adjustment costs within the model. The results therefore indicate a potential trade-off between environmental objectives and aggregate market output.

Table 6: CAFE equilibrium outcomes

Firm	**Sales under ICE investment**	**Sales under BEV investment**	**Optimal technology choice**	**Equilibrium sales**
Germany (DEU)	0.041174	0.041711	BEV	0.041711
Sweden (SWE)	0.041263	0.042315	BEV	0.042315
Total market	0.082437	0.084026	-	0.084026

Source: Author's calculations using MATLAB.

Table 7 confirms that the regulator's budget constraint is satisfied. The subsidy rate converges to $\sigma = 0.172414$, while tax revenues and subsidy expenditures are exactly equal. The policy therefore operates as a balanced-budget mechanism in which revenues collected from ICE vehicles are redistributed to support BEV adoption.

Table 7: Regulatory budget balance

Variable	Value
ICE tax (τ)	0.2000
BEV subsidy (σ)	0.172414
Tax revenue	0.333333
Subsidy expenditure	0.333333
Net revenue	-0.0000000000

Note: *The subsidy rate is determined endogenously to satisfy the balanced-budget constraint. Source: Author's calculations using MATLAB.*

4.1.3 Distributional Consequences of Regulation

Although both firms ultimately invest in BEV technology under CAFE regulation, the effects of the policy are not distributed evenly across firms. Table 8 compares equilibrium sales under laissez-faire conditions and under CAFE regulation. Germany experiences a reduction in equilibrium sales of approximately 0.0017 units, while Sweden experiences a substantially smaller reduction of approximately 0.0005 units. Total market sales also decline under regulation. The results therefore indicate that Germany bears a larger share of the adjustment costs associated with the transition towards low-emission technologies.

Table 8: Comparison of equilibrium sales across policy regimes

Firm	Laissez-faire equilibrium sales	CAFE equilibrium sales	Changes in sales
Germany (DEU)	0.0434	0.041711	-0.001689
Sweden (SWE)	0.0428	0.042315	-0.000485
Total market	0.0862	0.084026	-0.002174

Source: Author's calculations using MATLAB.

This asymmetry is important because it highlights a central mechanism underlying the policy dilemma examined in this thesis. While regulation successfully induces Germany to switch from ICE to BEV investment, the firm still performs worse than under the laissez-faire benchmark. Compliance with regulation therefore does not necessarily imply that firms benefit from regulation. The results suggest that firms adversely affected by environmental regulation may have incentives to oppose stricter standards, lobby for regulatory concessions or support policy delays, even when they ultimately comply with the policy once implemented. Consequently, environmental regulation may create winners and losers among firms, generating political pressure that could weaken future policy commitments.

The distributional effects identified here are particularly relevant for understanding regulatory credibility. If firms expect that policymakers may respond to political pressure by weakening or postponing future regulations, the incentive to undertake costly and irreversible investments in low-emission technologies may be reduced. The results therefore provide an important link between environmental regulation, firm incentives and the broader issue of policy credibility.

4.1.4 Strategic CAFE Scenario

The final simulation examines whether a stable equilibrium can emerge in which Germany (DEU) continues to invest in ICE technology while Sweden (SWE) invests in BEV technology under CAFE regulation. The purpose of this scenario is to investigate whether a firm with an initial comparative advantage in ICE production may continue to favour the incumbent technology despite the introduction of environmental regulation.

As in the previous simulation, the regulator imposes an ICE tax of $\tau = 0.2$ and determines the BEV subsidy endogenously to satisfy the balanced-budget condition. Table 9 confirms that the regulator's budget constraint remains satisfied, with a subsidy rate of $\sigma = 0.176152$. Tax revenues and subsidy expenditures are exactly equal, indicating that the policy remains self-financing.

Table 9: Regulatory budget under the strategic ICE-BEV scenario

Variable	**Value**
ICE tax (τ)	0.2000
BEV subsidy (σ)	0.176152
Tax revenue	0.342105
Subsidy expenditure	0.342105
Net revenue	-0.00000

Source: Author's calculations using MATLAB.

However, the assumed ICE-BEV configuration is not self-confirming. Table 10 shows that Germany achieves higher equilibrium sales under BEV investment (0.041792) than under ICE investment (0.041247). Sweden likewise continues to achieve higher sales under BEV investment than under ICE investment. Consequently, both firms prefer BEV investment, implying that the ICE-BEV configuration does not constitute a stable equilibrium under the baseline parameter values.

The results indicate that CAFE regulation remains sufficiently strong to alter Germany's investment incentives despite its initial comparative advantage in ICE production. Once the policy is introduced, BEV investment becomes the preferred strategy for both firms, leading once again to a common BEV-BEV equilibrium.

Table 10: Equilibrium technology choices under the strategic ICE-BEV scenario

Firm	Sales under ICE investment	Sales under BEV investment	Optimal technology choice	Equilibrium sales
Germany (DEU)	0.041247	0.041792	BEV	0.041792
Sweden (SWE)	0.041351	0.042412	BEV	0.042412
Total market	0.082598	0.084204	-	0.084204

Source: Author's calculations using MATLAB.

Table 11 further shows that total market sales under the assumed ICE-BEV configuration (0.083659) are lower than under the equilibrium BEV-BEV outcome (0.084204). The BEV-BEV equilibrium therefore not only represents the individually optimal investment choice for both firms but also generates higher aggregate market sales within the model.

Table 11: Market outcomes under CAFE scenario

Outcome	Value
Germany sales (ICE assumption)	0.041247
Sweden sales (BEV assumption)	0.042412
Total market sales (assumed ICE-BEV)	0.083659
Total market sales (optimal BEV-BEV)	0.084204

Source: Author's calculations using MATLAB.

The findings suggest that environmental regulation does not fail because firms are unable or unwilling to invest in low-emission technologies. On the contrary, both firms ultimately choose BEV investment once regulation is implemented. However, Germany still achieves lower sales under CAFE regulation than under the laissez-faire benchmark. Consequently, a firm may comply with environmental regulation while simultaneously having incentives to oppose, delay or weaken the policy. The challenge therefore lies not in technological adaptation itself, but in the distributional consequences of regulation and the political incentives these consequences may create.

4.2 Robustness and Sensitivity Analysis

To evaluate the robustness of the model, several key parameters were varied, including consumer preferences for BEVs (α), BEV baseline production costs $(\bar{C}_B)$, BEV investment efficiency (δ_B) and the ICE tax rate (τ). The purpose is to examine whether the qualitative results depend on the baseline calibration or remain stable across alternative parameter values.

4.2.1 Consumer Preferences for BEVs

Table 12 and Figure 1 examine how changes in consumer preferences for BEVs affect firms' investment incentives.

Table 12. Sensitivity to BEV Consumer Preferences

Scenario	**Critical $(\boldsymbol{\alpha})$**	**Equilibrium Implication**
Laissez-faire	0.403	Germany switches from ICE to BEV
CAFE (BEV-BEV)	0.304	Germany switches from ICE to BEV
Strategic ICE-BEV	0.300	Germany remains in ICE only below this threshold

Note: *The critical threshold represents the value of the BEV preference parameter (α) at which Germany becomes indifferent between ICE and BEV investment. Values above the threshold favour BEV investment.*
Source: Author's calculations using MATLAB.

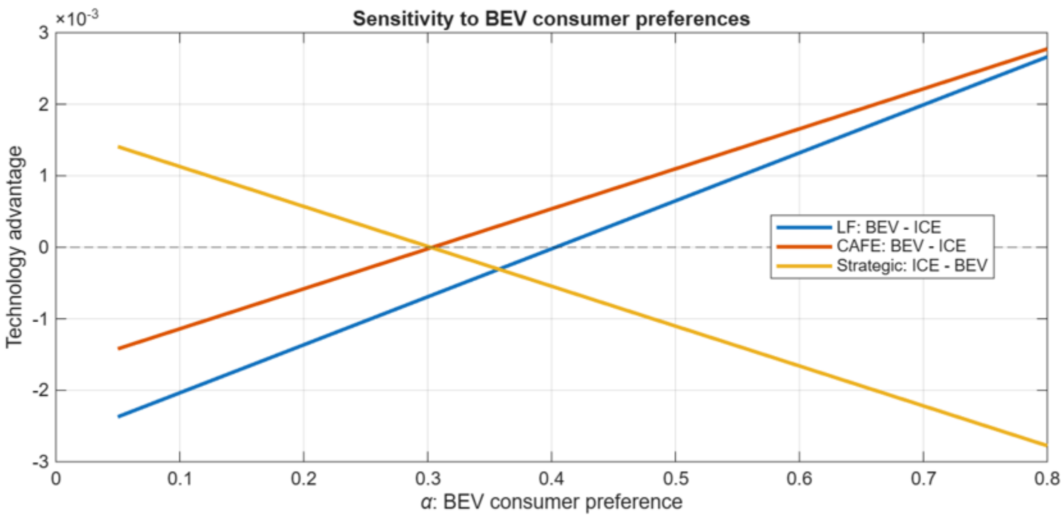

Figure 1. Sensitivity to BEV Consumer Preferences. Source: Author's calculations using MATLAB.

Figure 1 illustrates that the threshold for BEV adoption is substantially lower under CAFE regulation than under laissez-faire conditions. The results show that stronger consumer preferences for BEVs increase the relative attractiveness of BEV investment across all scenarios. Under laissez-faire conditions, Germany switches from ICE to BEV investment when the BEV preference parameter reaches approximately $\alpha = 0.403$. Under CAFE regulation, the corresponding threshold falls to $\alpha = 0.304$, indicating that environmental regulation reduces the level of consumer demand required to make BEV investment the preferred strategy. The strategic ICE-BEV scenario produces a similar threshold. Germany remains in ICE technology only when consumer preferences for BEVs remain below $\alpha = 0.300$. Once this threshold is exceeded, BEV investment becomes more attractive. These results suggest that consumer preferences and environmental regulation reinforce one another. Stronger consumer demand for electric vehicles increases firms' incentives to invest in BEVs, while regulation lowers the demand threshold required for this transition to occur.

4.2.2 BEV Production Costs

Table 13 and Figure 2 present the sensitivity analysis for BEV production costs.

Table 13. Sensitivity of Technology Choice to BEV Production Costs

Scenario	**Critical ($\bar{C}_B$)**	**Equilibrium Implication**
Laissez-faire (DEU)	59.11	Germany switches from BEV to ICE
Laissez-faire (SWE)	67.56	Sweden switches from BEV to ICE
CAFE (BEV–BEV)	85.71	BEV–BEV equilibrium remains stable up to this threshold
Strategic ICE–BEV	86.10	Germany remains in ICE above this threshold

***Note**: The critical threshold represents the BEV production cost at which the optimal technology choice changes. Higher values indicate that BEV investment remains attractive even when electric vehicle production becomes more costly.*
Source: Author's calculations using MATLAB.

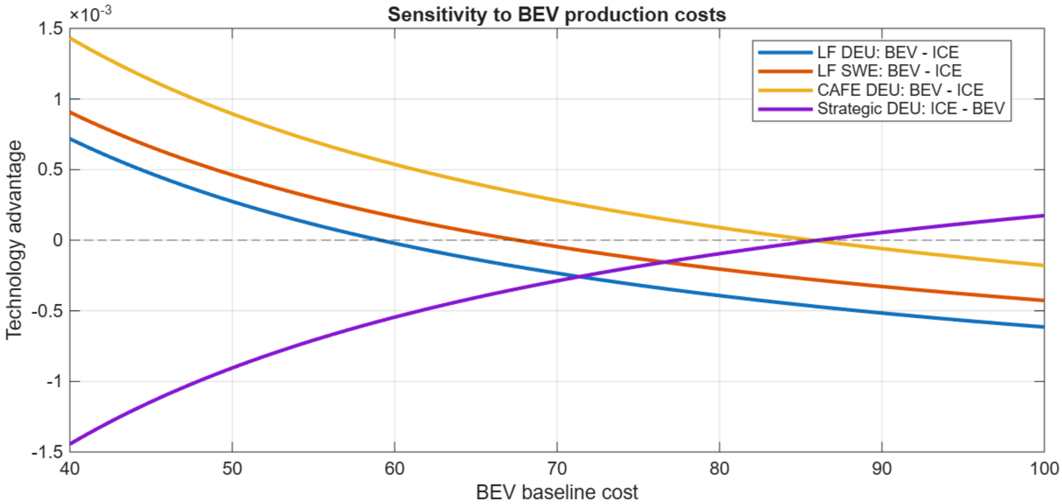

Figure 2. Sensitivity of Technology Choice to BEV Production Costs. Source: Author's calculations using MATLAB.

Figure 2 shows that environmental regulation allows BEV investment to remain attractive even at considerably higher production costs. As expected, higher BEV production costs reduce the attractiveness of BEV investment. Under laissez-faire conditions, Germany switches from BEV to ICE investment when BEV baseline costs exceed approximately 59.1, while Sweden switches at a higher threshold of approximately 67.6. This difference reflects Sweden's stronger comparative advantage in BEV technology. Under CAFE regulation the BEV-BEV equilibrium remains stable until BEV costs reach approximately 85.7. The strategic ICE-BEV scenario yields a similar threshold of approximately 86.1. This indicates that environmental regulation substantially increases the range of production costs over which BEV investment remains attractive.

The results therefore suggest that regulation can compensate for technological disadvantages by improving the relative returns to BEV investment. Even when electric vehicle production remains relatively costly, environmental policy can maintain incentives for technological transition.

4.2.3 BEV Investment Efficiency

Table 14 and Figure 3 examine the role of BEV investment efficiency.

Table 14. Sensitivity to BEV Investment Efficiency

Scenario	Critical δ_B	Equilibrium Implication
Laissez-faire	0.895	Germany prefers BEV below this threshold

CAFE (BEV–BEV)	0.925	BEV-BEV remains stable below this threshold
Strategic ICE–BEV	0.928	Germany remains in ICE above this threshold

***Note**: The critical threshold represents the value of the BEV investment factor (δ_B) at which firms become indifferent between alternative technology investments. Lower values of δ_B correspond to more effective BEV investments and larger reductions in production costs.*

Source: Author's calculations using MATLAB.

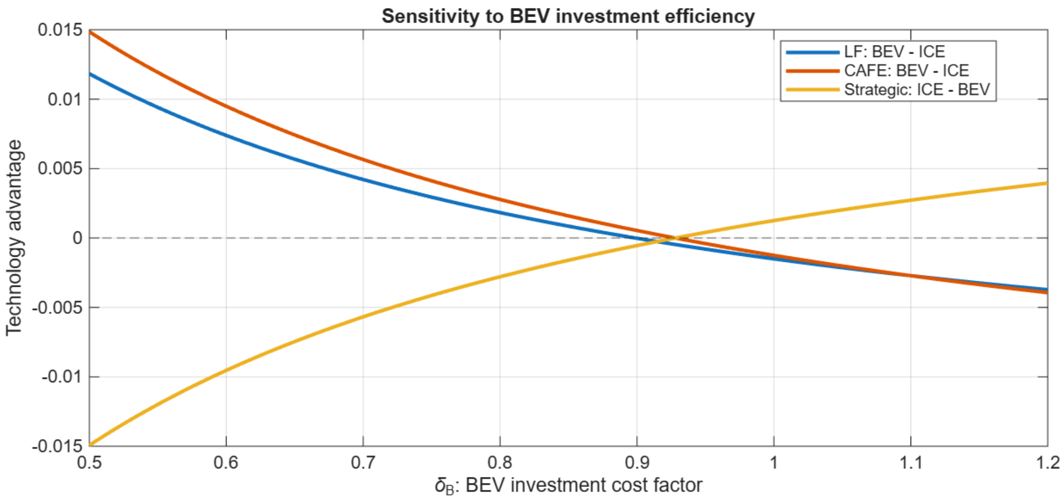

Figure 3. Sensitivity to BEV Investment Efficiency. Source: Author's calculations using MATLAB.

Figure 3 demonstrates that the attractiveness of BEV investment is highly sensitive to investment efficiency. The analysis shows that more efficient BEV investment strengthens incentives to adopt electric vehicle technology. Under laissez-faire conditions, Germany prefers BEV investment whenever the BEV investment factor remains below approximately $\delta_B = 0.895$. Under CAFE regulation, the BEV-BEV equilibrium remains stable up to approximately $\delta_B = 0.925$. The strategic ICE-BEV scenario generates a similar threshold of approximately $\delta_B = 0.928$. Above this level, BEV investment becomes insufficiently effective at reducing production costs, making ICE investment relatively more attractive. As illustrated in Figure 3, the technology advantage declines monotonically as BEV investment becomes less effective.

These findings are consistent with the central mechanism of the model. Investment lowers production costs, lower costs improve competitiveness and improved competitiveness increases equilibrium sales. Consequently, the effectiveness of technology investment plays an important role in determining firms' willingness to adopt BEV technology.

4.2.4 ICE Tax Rate

Table 15 and Figure 4 analyse the sensitivity of the results to changes in the ICE tax rate.

Table 15. Sensitivity to the ICE Tax Rate

Scenario	**Critical ICE Tax Rate (τ)**	**Equilibrium Implication**
CAFE (BEV–BEV equilibrium)	0.007	Germany switches from ICE to BEV
Strategic ICE–BEV	0.000	No stable ICE–BEV equilibrium emerges for any positive tax rate

Note*: The critical threshold represents the ICE tax rate at which Germany becomes indifferent between ICE and BEV investment. Tax rates above the threshold favour BEV investment.*
Source: Author's calculations using MATLAB.

The results show that even relatively small tax rates are sufficient to alter Germany's investment incentives. Under the CAFE scenario, Germany switches from ICE to BEV investment once the tax rate exceeds approximately $\tau = 0.007$. The strategic ICE-BEV scenario does not generate a stable mixed-technology equilibrium for any positive tax rate. Figure 4 demonstrates that even small increases in the ICE tax rate improve the relative attractiveness of BEV investment. The threshold occurs at a very low tax rate, indicating that the qualitative results are not dependent on unusually stringent environmental regulation.

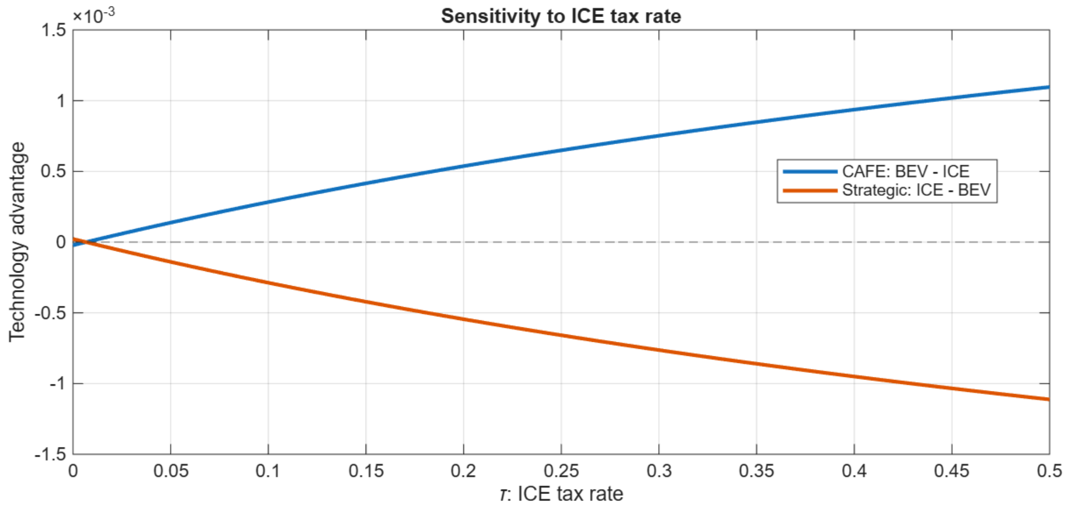

Figure 4. Sensitivity to ICE Tax Rate. Source: Author's calculations using MATLAB.

Figure 4 highlights that even relatively small ICE taxes are sufficient to shift Germany's investment incentives towards BEVs. This finding highlights the importance of policy incentives within the model. Even modest increases in the relative cost of ICE vehicles can shift firms' investment decisions toward BEVs. The results therefore suggest that the qualitative conclusions of the model do not depend on an unusually stringent regulatory intervention.

Overall, the sensitivity analysis supports the robustness of the baseline results. While the exact threshold values vary across parameter specifications, the central mechanism remains unchanged. Environmental regulation consistently strengthens incentives for BEV investment, while firms with different technological advantages continue to experience the effects of regulation asymmetrically.

5. Discussion

The purpose of this thesis is to shed light on a policy dilemma in environmental regulation: how can policymakers encourage firms to undertake costly and largely irreversible investments in low-emission technologies when future regulatory commitments may not be fully credible? The results show that CAFE-style regulation can redirect investment incentives toward BEV technology, but also that the effects of regulation are distributed unevenly across firms. This asymmetry is central to understanding why environmental regulation may generate political resistance even when firms ultimately comply with the policy.

5.1 Environmental regulation and technological transition

The main result is that CAFE-style regulation changes firms' investment incentives. Under laissez-faire conditions, firms invest according to their technological comparative advantages, DEU invests in ICE technology, while SWE invests in BEV technology. Once CAFE regulation is introduced, both firms invest in BEV technology. This suggests that environmental regulation can shift investment incentives away from incumbent technologies and toward low-emission alternatives. This result is consistent with the broader literature on environmental regulation and technological change. Porter and van der Linde (1995) argue that well-designed environmental regulation may stimulate innovation and efficiency improvements, while Jaffe and Palmer (1997) and Lanoie et al. (2011) show that environmental regulation can affect firms' innovation incentives. In the context of the automobile industry, the model's results are also consistent with studies showing that fleet emission standards influence firm behaviour, product portfolios and technology choices (Klier & Linn 2012; Jenn et al. 2016; Reynaert 2021). The model also shows that regulation is not costless. Total market sales are lower under CAFE regulation than under laissez-faire. This does not imply that regulation is ineffective, but rather that technological transition may involve adjustment costs. The result therefore supports the idea that environmental regulation can promote cleaner technologies while simultaneously creating short-run economic costs for affected firms.

5.2 Distributional effects and firm heterogeneity

A second key result is that the costs of regulation are not evenly distributed across firms. Although both firms switch to BEV investment under CAFE regulation, DEU experiences a larger reduction in equilibrium sales than SWE. This reflects the fact that DEU's initial comparative advantage lies in ICE production, while SWE's technological position is more aligned with the regulatory objective. This result highlights the importance of firm heterogeneity. Much of the literature on environmental regulation focuses on aggregate effects, such as emission reductions or innovation outcomes. The model developed in this thesis shows that regulation may also redistribute relative advantages between firms. Firms whose existing capabilities are aligned with the transition may face lower adjustment costs, while firms more strongly tied to incumbent technologies may experience larger losses. This finding is relevant for interpreting industry responses to environmental regulation. Firms may comply with regulation once it is implemented, but compliance does not necessarily mean that firms benefit from the policy. A firm can adapt to stricter regulation and still prefer a weaker regulatory environment. This distinction is important because it helps explain why environmental regulation may generate opposition even when firms are technically able to adjust.

5.3 Regulatory credibility and hold-up problems

The model does not show that CAFE regulation fails to induce BEV investment. On the contrary, the policy succeeds in shifting both firms toward BEV technology under the baseline calibration. The credibility problem instead arises because regulation creates asymmetric adjustment costs. DEU complies with the policy but receives lower sales than under laissez-faire. This creates an incentive to oppose, delay or weaken the regulation. This mechanism is closely related to the literature on time inconsistency and regulatory hold-up. Kydland and Prescott (1977) show that policies considered optimal before private actors make decisions may no longer be optimal after those decisions have been taken. Schelling (1958) similarly emphasizes the importance of credible commitment. In the context of irreversible investment, Pindyck (1991) show that uncertainty can delay or reduce investment when firms cannot recover sunk costs. The model's results are particularly close to the mechanism described by Gersbach and Glazer (1999). Their regulatory hold-up framework shows that firms may underinvest if they expect regulators to relax environmental policy after investments have become sunk. This thesis applies a similar logic to the European automobile transition. The results suggest that firms' expectations about future policy credibility may be affected by the distributional consequences of regulation. If firms believe that policymakers will respond to industry pressure by weakening future standards, investment incentives may be reduced even before regulation is implemented.

5.4 Policy implications

The results have several policy implications. Environmental regulation can affect technology investment incentives, but policy stringency alone may not be sufficient. If firms expect future policy weakening, the credibility of regulation becomes as important as its formal design. Announcing ambitious environmental targets may therefore be less effective if firms believe that the targets will later be postponed or revised. The results also show that policymakers need to consider the distributional consequences of regulation. The model shows that regulation may create winners and losers among firms depending on their technological starting points. Firms that are disadvantaged by regulation may have incentives to lobby for delays, exemptions or weaker standards. This suggests that credible environmental policy requires not only clear targets but also political mechanisms that make future implementation believable. The results suggest that transitional support may strengthen policy credibility. If policymakers reduce adjustment costs for firms with strong incumbent-technology advantages, political resistance to regulation may weaken. This could make future policy commitments more credible and thereby strengthen incentives for irreversible investment in low-emission technologies. In summary, the results are relevant to the recent European debate on fleet emission standards. The postponement of stricter standards illustrates how political and economic pressure may lead regulators to revise previously announced policies. From the perspective of the model, such policy adjustments may have broader consequences than simply giving firms more time to adapt. They may also affect expectations about future regulatory commitment, which in turn can influence current investment incentives.

5.5 Limitations

The results of this thesis should be interpreted as theoretical illustrations rather than quantitative predictions. Because the model relies on stylized assumptions and parameter values, it is designed to illustrate the economic mechanisms linking environmental regulation, regulatory credibility and irreversible investment rather than to predict future developments in the European automobile industry.

Several simplifying assumptions influence the interpretation of the results. First, the assumption of perfect competition abstracts from market power, product differentiation and strategic pricing. Consequently, the model cannot capture how these factors may interact with environmental regulation and investment decisions. Second, the stylized representation of the industry, consisting of two representative European firms and one exogenous Chinese competitor, means that the results illustrate general economic mechanisms rather than firm- or country-specific outcomes. Finally, the model abstracts from uncertainty regarding technological progress, consumer preferences, macroeconomic conditions and future regulation, all of which may influence investment decisions in practice.

5.6 Future research

Several extensions could strengthen the analysis and increase its realism. Future research could introduce imperfect competition and profit-maximising firms, allowing market power, strategic pricing and product differentiation to interact with environmental regulation. The regulator's objective function could also be modelled explicitly to examine when policy commitment becomes difficult to sustain. Incorporating uncertainty regarding regulation, technological development, consumer demand and energy prices would further improve the framework by capturing the interaction between policy credibility and investment risk. Finally, empirical research could investigate whether firms more adversely affected by environmental regulation are more likely to lobby for policy delays or weaker environmental standards, providing evidence on the political mechanisms underlying the regulatory commitment problem.

6. Conclusion

This thesis examined how environmental regulation and regulatory credibility influence irreversible technology investment in the European automobile industry using a stylized dynamic game. The results show that, under laissez-faire conditions, firms invest according to their technological comparative advantages, whereas CAFE-style regulation redirects both firms towards BEV investment. However, the costs of regulation are distributed unevenly across firms. Although Germany complies with the regulation, it experiences a larger reduction in sales than Sweden, creating stronger incentives to oppose or delay stricter environmental policies. The findings suggest that the effectiveness of environmental regulation depends not only on policy design but also on policy credibility. If firms expect future regulations to be weakened or postponed, incentives to undertake irreversible investments may be reduced. Achieving the transition to low-emission transport therefore requires environmental regulation that is both stringent and credible.

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Appendix 1

Appendix 1 presents the MATLAB program used to solve the laissez-faire benchmark scenario.

```
==========================================================
% LAISSEZ-FAIRE - TECHNOLOGY CHOICE MODEL
% Countries: 1 = Germany (DEU), 2 = Sweden (SWE)
==========================================================
clear;
clc;

%% ==========================
% PARAMETERS
%% ==========================

countryNames = ["Germany","Sweden"];

% Preferences
alpha = [0.40, 0.40];   % BEV preference
beta  = [0.10, 0.10];   % Chinese BEV competition

% Market size / income
W = [2, 2];

% Baseline costs
CbarA = [35, 40];       % ICE costs
CbarB = [60, 50];       % BEV costs

% Investment efficiency
deltaA = [0.95, 0.95];  % ICE investment efficiency
deltaB = [0.90, 0.90];  % BEV investment efficiency

%% ==========================
% STORAGE
%% ==========================

chosenSales = zeros(1,2);
chosenTech  = strings(1,2);

%% ==========================
% TECHNOLOGY CHOICE
```

```
%% ========================

for i = 1:2

    sA = 1 - alpha(i) - beta(i);
    sB = alpha(i);

    % Sales if firm invests in ICE
    V_ICE = (sA / (CbarA(i)*deltaA(i)) + sB / CbarB(i)) * W(i);

    % Sales if firm invests in BEV
    V_BEV = (sA / CbarA(i) + sB / (CbarB(i)*deltaB(i))) * W(i);

    % Optimal choice
    if V_ICE > V_BEV
        choice = 'ICE investment';
        chosenSales(i) = V_ICE;
        chosenTech(i) = "ICE";

    elseif V_BEV > V_ICE
        choice = 'BEV investment';
        chosenSales(i) = V_BEV;
        chosenTech(i) = "BEV";

    else
        choice = 'Indifferent';
        chosenSales(i) = V_ICE;
        chosenTech(i) = "Indifferent";
    end

    % Print country results
    fprintf('\n========================================\n');
    fprintf('Country: %s\n', countryNames(i));
    fprintf('----------------------------------------\n');
    fprintf('Sales if ICE investment: %.5f\n', V_ICE);
    fprintf('Sales if BEV investment: %.5f\n', V_BEV);
    fprintf('Optimal choice: %s\n', choice);

end

%% ========================
```

```
% TOTAL SALES
%% =========================

totalSales = sum(chosenSales);

fprintf('\n\n======================================\n');
fprintf('TOTAL SALES UNDER OPTIMAL LF CHOICES\n');
fprintf('======================================\n');

fprintf('\nGermany:\n');
fprintf('Chosen technology: %s\n', chosenTech(1));
fprintf('Sales: %.4f\n', chosenSales(1));

fprintf('\nSweden:\n');
fprintf('Chosen technology: %s\n', chosenTech(2));
fprintf('Sales: %.4f\n', chosenSales(2));

fprintf('\n--------------------------------------\n');
fprintf('Total LF market sales: %.4f\n', totalSales);
fprintf('======================================\n');
```

Appendix 2

Appendix 2 presents the MATLAB program used to solve the CAFE regulation scenario.

```
============================================================
% CAFE SCENARIO 1: CREDIBLE STRONG POLICY
% Assumption: DEU = BEV, SWE = BEV
%
% Step 1: Set tau = 0.20
% Step 2: Find sigma such that regulator breaks even
% Step 3: Check if BEV-BEV is actually optimal
%%
============================================================

clear; clc;

%% ========================
% PARAMETERS
%% ========================

countryNames = ["Germany","Sweden"];

tau = 0.20;   % ICE tax

alpha = [0.40, 0.40];
beta  = [0.10, 0.10];
W     = [2, 2];

CbarA = [35, 40];   % ICE baseline cost
CbarB = [60, 50];   % BEV baseline cost

deltaA = [0.95, 0.95];
deltaB = [0.90, 0.90];

tol = 1e-10;
maxIter = 10000;

%% ========================
% STEP 1: FIND SIGMA GIVEN BEV-BEV
%% ========================
```

```
sigma_low  = 0;
sigma_high = 0.99;

for iter = 1:maxIter

    sigma = (sigma_low + sigma_high)/2;

    taxRevenue = 0;
    subsidyCost = 0;

    totalICE = 0;
    totalBEV = 0;
    firmSales = zeros(1,2);

    for i = 1:2

        sA = 1 - alpha(i) - beta(i);
        sB = alpha(i);

        % Under assumed BEV investment:
        % ICE is not invested in, BEV is invested in
        P_A = CbarA(i) * (1 + tau);
        P_B = CbarB(i) * deltaB(i) * (1 - sigma);

        Q_A = sA * W(i) / P_A;
        Q_B = sB * W(i) / P_B;

        taxRevenue  = taxRevenue  + tau   * CbarA(i) * Q_A;
        subsidyCost = subsidyCost + sigma * CbarB(i) * deltaB(i) * Q_B;

        totalICE = totalICE + Q_A;
        totalBEV = totalBEV + Q_B;

        firmSales(i) = Q_A + Q_B;

    end

    netRevenue = taxRevenue - subsidyCost;

    if abs(netRevenue) < tol
        break;
```

```
    end

    if netRevenue > 0
        sigma_low = sigma;
    else
        sigma_high = sigma;
    end

end

totalSales = sum(firmSales);

%% ==========================
% PRINT BUDGET RESULT
%% ==========================

fprintf('\n========================================\n');
fprintf('CAFE SCENARIO 1: ASSUMED BEV-BEV\n');
fprintf('========================================\n');

fprintf('Tau: %.4f\n', tau);
fprintf('Budget-balancing sigma: %.6f\n', sigma);

fprintf('\n--- Regulator budget ---\n');
fprintf('Tax revenue: %.6f\n', taxRevenue);
fprintf('Subsidy cost: %.6f\n', subsidyCost);
fprintf('Net revenue: %.10f\n', netRevenue);

fprintf('\n--- Market outcome under assumed BEV-BEV ---\n');
fprintf('Germany sales: %.6f\n', firmSales(1));
fprintf('Sweden sales: %.6f\n', firmSales(2));
fprintf('Total ICE sales: %.6f\n', totalICE);
fprintf('Total BEV sales: %.6f\n', totalBEV);
fprintf('Total market sales: %.6f\n', totalSales);

%% ==========================
% STEP 2: CHECK WHETHER BEV-BEV IS OPTIMAL
%% ==========================

fprintf('\n========================================\n');
fprintf('CHECK TECHNOLOGY CHOICE GIVEN SIGMA\n');
```

```
fprintf('=====================================\n');

chosenTech = strings(1,2);
chosenSales = zeros(1,2);

for i = 1:2

   sA = 1 - alpha(i) - beta(i);
   sB = alpha(i);

   % If firm invests in ICE:
   % ICE cost reduced, BEV cost not reduced
   V_ICE = ...
      (sA / (CbarA(i)*deltaA(i)*(1+tau)) ...
     + sB / (CbarB(i)*(1-sigma))) * W(i);

   % If firm invests in BEV:
   % ICE cost not reduced, BEV cost reduced
   V_BEV = ...
      (sA / (CbarA(i)*(1+tau)) ...
     + sB / (CbarB(i)*deltaB(i)*(1-sigma))) * W(i);

   if V_BEV > V_ICE
      chosenTech(i) = "BEV";
      chosenSales(i) = V_BEV;
   elseif V_ICE > V_BEV
      chosenTech(i) = "ICE";
      chosenSales(i) = V_ICE;
   else
      chosenTech(i) = "Indifferent";
      chosenSales(i) = V_BEV;
   end

   fprintf('\n%s\n', countryNames(i));
   fprintf('Sales if ICE investment: %.6f\n', V_ICE);
   fprintf('Sales if BEV investment: %.6f\n', V_BEV);
   fprintf('Optimal choice: %s\n', chosenTech(i));

end

%% =========================
```

```
% FINAL CHECK
%% =========================

fprintf('\n=====================================\n');
fprintf('FINAL SCENARIO CHECK\n');
fprintf('=====================================\n');

if chosenTech(1) == "BEV" && chosenTech(2) == "BEV"
    fprintf('SUCCESS: BEV-BEV is self-confirming.\n');
    fprintf('The assumed scenario holds.\n');
else
    fprintf('FAIL: BEV-BEV is not self-confirming.\n');
    fprintf('The assumed scenario does not hold.\n');
end

fprintf('\nChosen Germany technology: %s\n', chosenTech(1));
fprintf('Chosen Sweden technology: %s\n', chosenTech(2));
fprintf('Total sales under chosen technologies: %.6f\n', sum(chosenSales));
fprintf('=====================================\n');
```

Appendix 3

Appendix 3 presents the MATLAB program used to analyse the strategic ICE–BEV scenario.

```
===========================================================
% CAFE SCENARIO 2: STRATEGIC DEU
% Assumption: DEU = ICE, SWE = BEV
%
% Step 1: Set tau = 0.20
% Step 2: Find sigma such that regulator breaks even
% Step 3: Check if ICE-BEV is actually optimal
%%
===========================================================

clear; clc;

%% ==========================
% PARAMETERS
%% ==========================

countryNames = ["Germany","Sweden"];

tau = 0.20;   % ICE tax

alpha = [0.40, 0.40];
beta  = [0.10, 0.10];
W     = [2, 2];

CbarA = [35, 40];   % ICE baseline cost
CbarB = [60, 50];   % BEV baseline cost

deltaA = [0.95, 0.95];
deltaB = [0.90, 0.90];

tol = 1e-10;
maxIter = 10000;

%% ==========================
% STEP 1: FIND SIGMA GIVEN DEU=ICE, SWE=BEV
%% ==========================
```

```
sigma_low  = 0;
sigma_high = 0.99;

for iter = 1:maxIter

    sigma = (sigma_low + sigma_high)/2;

    taxRevenue = 0;
    subsidyCost = 0;

    totalICE = 0;
    totalBEV = 0;
    firmSales = zeros(1,2);

    for i = 1:2

        sA = 1 - alpha(i) - beta(i);
        sB = alpha(i);

        if i == 1
            % Germany assumed ICE investment
            P_A = CbarA(i) * deltaA(i) * (1 + tau);
            P_B = CbarB(i) * (1 - sigma);

        elseif i == 2
            % Sweden assumed BEV investment
            P_A = CbarA(i) * (1 + tau);
            P_B = CbarB(i) * deltaB(i) * (1 - sigma);
        end

        Q_A = sA * W(i) / P_A;
        Q_B = sB * W(i) / P_B;

        taxRevenue  = taxRevenue  + tau   * CbarA(i) * Q_A;
        subsidyCost = subsidyCost + sigma * P_B/(1-sigma) * Q_B;

        totalICE = totalICE + Q_A;
        totalBEV = totalBEV + Q_B;

        firmSales(i) = Q_A + Q_B;
```

```
    end

    netRevenue = taxRevenue - subsidyCost;

    if abs(netRevenue) < tol
        break;
    end

    if netRevenue > 0
        sigma_low = sigma;
    else
        sigma_high = sigma;
    end

end

totalSales = sum(firmSales);

%% ========================
% PRINT BUDGET RESULT
%% ========================

fprintf('\n======================================\n');
fprintf('CAFE SCENARIO 2: ASSUMED DEU=ICE, SWE=BEV\n');
fprintf('======================================\n');

fprintf('Tau: %.4f\n', tau);
fprintf('Budget-balancing sigma: %.6f\n', sigma);

fprintf('\n--- Regulator budget ---\n');
fprintf('Tax revenue: %.6f\n', taxRevenue);
fprintf('Subsidy cost: %.6f\n', subsidyCost);
fprintf('Net revenue: %.10f\n', netRevenue);

fprintf('\n--- Market outcome under assumed ICE-BEV ---\n');
fprintf('Germany sales: %.6f\n', firmSales(1));
fprintf('Sweden sales: %.6f\n', firmSales(2));
fprintf('Total ICE sales: %.6f\n', totalICE);
fprintf('Total BEV sales: %.6f\n', totalBEV);
fprintf('Total market sales: %.6f\n', totalSales);
```

```
%% ========================
% STEP 2: CHECK WHETHER ICE-BEV IS OPTIMAL
%% ========================

fprintf('\n========================================\n');
fprintf('CHECK TECHNOLOGY CHOICE GIVEN SIGMA\n');
fprintf('========================================\n');

chosenTech = strings(1,2);
chosenSales = zeros(1,2);

for i = 1:2

   sA = 1 - alpha(i) - beta(i);
   sB = alpha(i);

   % If firm invests in ICE
   V_ICE = ...
      (sA / (CbarA(i)*deltaA(i)*(1+tau)) ...
     + sB / (CbarB(i)*(1-sigma))) * W(i);

   % If firm invests in BEV
   V_BEV = ...
      (sA / (CbarA(i)*(1+tau)) ...
     + sB / (CbarB(i)*deltaB(i)*(1-sigma))) * W(i);

   if V_BEV > V_ICE
      chosenTech(i) = "BEV";
      chosenSales(i) = V_BEV;
   elseif V_ICE > V_BEV
      chosenTech(i) = "ICE";
      chosenSales(i) = V_ICE;
   else
      chosenTech(i) = "Indifferent";
      chosenSales(i) = V_BEV;
   end

   fprintf('\n%s\n', countryNames(i));
   fprintf('Sales if ICE investment: %.6f\n', V_ICE);
   fprintf('Sales if BEV investment: %.6f\n', V_BEV);
   fprintf('Optimal choice: %s\n', chosenTech(i));
```

```
end

%% ========================
% FINAL CHECK
%% ========================

fprintf('\n========================================\n');
fprintf('FINAL SCENARIO CHECK\n');
fprintf('========================================\n');

if chosenTech(1) == "ICE" && chosenTech(2) == "BEV"
    fprintf('SUCCESS: DEU=ICE and SWE=BEV is self-confirming.\n');
    fprintf('The assumed strategic scenario holds.\n');
else
    fprintf('FAIL: DEU=ICE and SWE=BEV is not self-confirming.\n');
    fprintf('The assumed scenario does not hold.\n');
end

fprintf('\nChosen Germany technology: %s\n', chosenTech(1));
fprintf('Chosen Sweden technology: %s\n', chosenTech(2));
fprintf('Total sales under chosen technologies: %.6f\n', sum(chosenSales));
fprintf('========================================\n');
```

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