Inducing Energy Network Innovation for Green Transition in the European Union

A Tripartite Evolutionary Game Model

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Abstract

The aim of this thesis is to investigate how energy networks in the European Union can be encouraged to increase innovation with decarbonization goals. This is done by analysing a tripartite evolutionary game model with the European Commission, national regulators and energy networks in the European Union being the three groups of players in the game. I find that the only evolutionary stable state of the game is the state where all three groups of players choose their cooperation strategies. For the Commission and the regulators, this involves changing regulations and regulatory mechanisms, respectively, in order to induce innovation. For the energy networks, it involves investing in innovation with decarbonization goals. On the basis of the assumption that the initial probability of the Commission choosing its cooperation strategy is relatively high and the initial probabilities of the regulators and the energy networks choosing their cooperation strategies is relatively low, numerical simulations suggest that the convergence rate to the evolutionary stable state can be increased if the Commission increases the probability of the energy networks receiving some average external funding and the penalty imposed on regulators in case they do not change their regulatory mechanisms in order to induce innovation. Altogether, the Commission plays a significant role in reaching the stable state.

Contents

Chapter 1

Introduction

In December 2019, the European Green Deal was presented by the European Commission, which is referred to as the Commission throughout this thesis (European Commission, n.d.-a). Through this initiative, the European Union, abbreviated as the EU, set the ambitious goal to become the first climate-neutral continent by 2050. This goal was written into law by July 2021 when the European Climate Law entered into force (European Commission, n.d.-d). According to numbers from the Commission, more than 75% of greenhouse gas emissions in the EU come from the production and use of energy (European Commission, n.d.-c). Thus, in order to reach the goals of the European Green Deal, decarbonizing the energy sector is an essential step. A fundamental part of this is developing a well-planned and integrated energy infrastructure (European Commission, 2021). This is the main objective of the Trans-European Networks for Energy Regulation (European Commission, n.d.-h). Through this, chosen infrastructure projects known as Projects of Common Interest are identified from Ten-Year Network Development Plans. These plans are prepared by the European Network for Transmission System Operators, whose responsibility is to coordinate the work of energy networks across the Member States, identify investment gaps and coordinate the planning of network investments (European Commission, n.d.-g).

Nonetheless, despite the Commission's efforts to integrate the energy infrastructure with the objective of decarbonizing the sector, there is still work to be done. It is widely acknowledged in the academic literature that innovation is key to achieving the green transition (Jamasb et al., 2020; Poudineh et al., 2020; Rong et al., 2022). An innovation can be defined as "*the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations*" (OECD/Eurostat, 2005, para. 146). In order to arrive at the implementation of innovations, innovation activities such as research and development, abbreviated as R&D, are conducted (OECD/Eurostat, 2005). However, the energy sector is one of the least R&D intensive, and R&D spending in the sector has decreased further since the liberalisation of the sector in the 1990s (Jamasb & Pollitt, 2008). Especially the network segments lack innovation due to the natural monopoly characteristics of the energy networks (Poudineh et al., 2020). In order to examine how these challenges can be overcome, I have developed the following research question which will be investigated through this thesis:

How can energy networks in the European Union be encouraged to increase innovation with decarbonization goals?

The term *innovation* here refers to innovation activities such as R&D that are conducted with the purpose of implementing innovations as described above. In general, when used throughout this thesis, *innovation* will mean innovation activities. Furthermore, whenever referring to the energy sector or actors related to it, it concerns the energy sector in the EU unless otherwise stated. While this question has already been examined in the academic literature (see, e.g., Jamasb et al., 2020), I take a different approach in this thesis and build on the existing research by analysing a tripartite evolutionary game with the Commission, the national regulators and the energy networks being the three groups of players. By using this approach, I can analyse the strategic interactions of the various stakeholders and the question of whether it is possible to reach a stable state where energy networks invest in innovation with decarbonization goals. I find that the only evolutionary stable state of the game involves that the Commission changes its legislation in order to induce innovation with decarbonization goals, the regulators use a regulatory mechanism that incentivizes investment in innovation by for example taking into account the risk profile of the projects, and energy networks invest in innovation with decarbonization goals. However, this stable state relies on the assumption that penalties exceeding the costs of taking the necessary measures for encouraging the energy networks to invest in innovation will be imposed on the Commission and the regulators, respectively, if they change their strategies.

Through this study, I also contribute to the area of research that uses evolutionary game theory for studying environmental regulation since the majority of this research deals with the case of China. The remainder of the thesis proceeds as follows. Chapter 2 reviews the relevant academic literature. Chapter 3 gives an outline of the internal energy market in the EU. Chapter 4 describes the methodology and how the game is set up. In chapter 5, the equilibrium points of the game are derived, a stability analysis is conducted and numerical simulations are performed. In chapter 6, policy implications of the results are discussed. Furthermore, limitations of the game and the methodology are presented, and future research suggestions are offered. Chapter 7 concludes.

Chapter 2

Literature Review

Through this thesis, I investigate the research question posed in chapter 1. Overall, this question lies at the interface of three research areas: regulation of (natural) monopolies, inducing innovation in regulated monopolies and employing evolutionary game theory in environmental regulation. In sections 2.1, 2.2 and 2.3, I review the existing research on each of these areas.

2.1 Regulation of (Natural) Monopolies

In the neoclassical work by Dupuit (1952) and Hotelling (1938), it is suggested that optimal regulation of natural monopolies involves setting prices at marginal cost while paying the firm a subsidy corresponding to their fixed costs in order to induce them to produce. However, a major issue when regulating monopolies is getting the monopolist to correctly report its costs. One of the most cited studies on regulation of monopolies under asymmetric information is by Baron and Myerson (1982). They derive an optimal regulatory policy which maximizes social welfare and incentivizes the monopolist to correctly report its costs. The main idea of the policy they propose is to use a subsidy to induce the monopolist to both produce and to truthfully reveal its costs. Thus, they add an additional function to the subsidy used for regulating the monopolist compared to the objective of paying a subsidy to a natural monopolist introduced in the complete-information case presented by Dupuit (1952) and Hotelling (1938) as described above. Baron and Myerson (1982) show that only incentive-compatible policies, i.e. policies where the monopolist has an incentive to report its costs truthfully, need to be considered by the regulator since these are at least as good as any non-incentive compatible policy. This means the regulatory instruments can be chosen as functions of the monopolist's true cost parameter.

The model developed by Baron and Besanko (1984) is an extension of that of Baron and Myerson (1982) in the sense that they also study a case of asymmetric information between the regulator and the firm but with the extra element of the regulator being able to, at some cost and after production, audit the costs incurred by the firm and impose a penalty if they find that the firm has misreported its costs ex ante. The verification of the private information of the firm from the audit is not assumed to be perfect, but still, they find the possibility of auditing to weakly improve welfare. Baron and

Besanko (1984) conclude that an optimal regulatory mechanism is to audit when the firm reports costs to be above some particular level and to demand a refund to the consumers when the audit shows that incurred costs are in fact lower than reported costs.

This study is related to that of Laffont and Tirole (1986) who also assume that the regulator can observe the cost of the firm ex post. However, in the model by Laffont and Tirole (1986), auditing is not costly, and the ex post cost level is not uncertain. They assume that the firm knows its efficiency ex ante. Then, after entering into a contract, it chooses an output and an effort level which together with some additive cost disturbance make up the cost level of the firm. Since the effort level of the firm is private information, there is a problem of moral hazard. The regulator observes the output and ex post cost level and lets the firm's reward depend on these two. Laffont and Tirole (1986) present two main conclusions. The first one is that the regulator can use a reward function that is linear in cost no matter the distribution of the cost disturbance. Their second main finding is that, due to the firm choosing whether to select a fixed-price or an incentive contract, the fraction of realized cost reimbursed to the firm decreases with the firm's output or increases with the firm's announced cost. It is evident that the conclusions of Laffont and Tirole (1986) differ from those of Baron and Besanko (1984) by higher reported costs being rewarded. However, due to the moral hazard issue, the firm is only partially reimbursed for its costs.

Lim and Yurukoglu (2018) come up with a different solution to the asymmetric information problem between monopolists and regulators. They study this problem, which they also point out to be a problem of moral hazard, as presented by Baron and Myerson (1982) and Laffont and Tirole (1986) as well as the time inconsistency problem of policymakers not being able to credibly commit to future policies and the interaction of these two forces with the political environment in the context of regulating the US electricity distribution industry, which is a natural monopoly. They find underinvestment in electricity distribution capital which they mention to be a result of the time inconsistency issue since the regulator cannot credibly commit to keeping a fair return on investments after investment costs are sunk. The moral hazard issue implies that the regulator cannot directly measure costly actions taken by the monopolist to reduce costs which is also the issue presented by Baron and Myerson (1982) and Laffont and Tirole (1986).

Lim and Yurukoglu (2018) specify and estimate a dynamic game theoretic model of the interaction between the regulator and the monopolist which captures both of these issues. They find that more conservative political environments, which they define as political environments that place a higher weight on the profits of the monopolist than on consumer surplus, suffer less from the time inconsistency problem but more from the moral hazard problem. Hence, the two effects can be captured by setting the rate-of-return policy to that of the most conservative regulator and by complementing this policy with minimum auditing requirements. The first part will mitigate the time inconsistency problem while the second part will improve the moral hazard problem, which is expected to be worsened by the more conservative regulatory policy (Lim & Yurukoglu, 2018).

Fiocco and Guo (2020) study the effect of regulatory risk, which corresponds to what Lim and Yurukoglu (2018) called time inconsistency, on vertical integration and upstream investment by a regulated firm. They find that regulatory risk can ex ante be socially beneficial when the regulatory policy is set after the vertical industry structure has been established. This contrasts with the study of Lim and Yurukoglu (2018) who find a connection between underinvestment and limited regulatory commitment. However, according to Fiocco and Guo (2020), the choice of vertical integration has a significant impact on whether regulatory risk is socially beneficial or not and should, according to them, be endogenized such that the effect of regulatory risk on investment activities can be investigated.

2.2 Inducing Innovation in Regulated Monopolies

In continuation of the literature on regulating monopolies, a corner of this research deals with designing regulatory mechanisms that induce innovation in regulated firms. Thus, this is closely related to the research question presented in chapter 1. One of the reasons why this relevant to investigate in relation to energy networks is that a significant decline in R&D spending in the energy sector followed the liberalisation of the sector as will be described further in section 3.1. Jamasb and Pollitt (2008) review the industrial organisation literature on R&D and innovation in order to examine the effect of the liberalisation of the electricity sector on R&D activities. They find that some of the reasons why the liberalisation led to a decline in R&D are a negative effect of decreased firm size, increased uncertainty, a pressure for short-term profitability and that the price cap regulation of networks after the liberalisation was not likely to induce R&D spending. Furthermore, based on their literature review, they conclude that the decline in R&D spending could have been predicted.

Cantner and Kuhn (1999) analyse the case of asymmetric information as presented in section 2.1 where the regulated firm has private information of production costs. Additionally, in the setting by Cantner and Kuhn (1999), the firm also has private information about the cost-reducing effect of R&D investments. The purpose of their study is to analyse how the technical progress – in their paper meaning process innovations – of a natural monopoly can be regulated in an asymmetric information case. They study two different cases. In the first case, they assume that the firm chooses its R&D level itself in order to maximize profits. However, due to the asymmetric information between the firm and the regulator, this R&D level is too high from the regulator's point of view since the firm will have an incentive to misreport its true type, meaning the regulator has to provide for both the R&D expenditures and the information rent transferred to the firm.

For this reason, in the second case studied, Cantner and Kuhn (1999) assume that the regulator can observe and set limits on the firm's R&D level. They use a mechanism design approach where they model the regulator as the social planner who wishes to maximize expected social welfare. They find that information rents gained by the firm in the first case can be reduced if the regulator sets a limit on the firm's R&D investments. They find this to improve social welfare since the decrease in consumer surplus, which is a result of the decrease in output and increase in price resulting from limiting the firm's R&D investments, is offset by the decrease in information rents, but they also mention the problematic of the regulator possibly finding it optimal to slow down instead of incentivizing technical progress with the aim of reducing information rents. Still, they find that in natural monopolies such as electric power transmission, optimal regulation schemes such as the ones developed in Cantner and Kuhn (1999) might be a second-best solution that could reduce the entry barrier of high sunk costs into the market.

Poudou and Thomas (2010) find that the results found by Cantner and Kuhn (1999) are only applicable to the case where R&D investments and efficiency are complements, meaning R&D is more advantageous to efficient agents. For this reason, they extend this work to the case where R&D investments and efficiency are substitutes, meaning R&D is more advantageous to inefficient agents. They point out that if the substitutability between efficiency and R&D investments is weak, the situation is similar to that of the complementary case, and it is not optimal to induce an inefficient agent to invest more in R&D than an efficient agent. However, if the substitutability between efficiency and R&D investments is instead strong, they find that inducing an inefficient agent to invest more in R&D than an efficient agent is optimal. This is due to a so-called catching up effect which implies that an increase in R&D investments by an inefficient agent leads to a sharp decrease in marginal costs of production. Hence, the efficiency gap between efficient and inefficient agents will be reduced ex post in this case.

Lewis and Yildirim (2002) extend the model by Baron and Myerson (1982) presented in section 2.1 and study how a monopolist with unknown costs can be induced to develop and adopt cost-saving technologies. Contrary to the other studies presented in this section, they study innovation through learning by doing and not through R&D investments, but they find that some of the same ideas could be applied to the case of R&D. The setting is one where a regulator acting on behalf of the consumers regulates a monopolist service supplier. They assume that regulatory agreements are renegotiated each period and that the monopolist's cost of service is made up of an intrinsic cost, which is publicly known, and a temporal cost, which is the monopolist's private information of current supply conditions.

They find that, in equilibrium, regulators reduce the firm's service payments following the reduction in supply costs. However, when the regulator demands more service, giving rise to more innovation due to an accelerated rate of learning, and the supply costs fall, the firm earns greater information rents due to its private information. For this reason, it still has incentives to develop and adopt cost-saving technologies despite the regulator reducing the service payments. This means the surplus from the innovation is divided between the monopolist and the consumers, and thus, both parties benefit from the innovation. Hence, the findings by Lewis and Yildirim (2002) contradict those of Cantner and Kuhn (1999) who found the increased information rents gained by the firm as a result of the cost-reducing innovation to result in reduced consumer surplus. However, here it should be noted that Cantner and Kuhn (1999) study innovation through R&D investments while Lewis and Yildirim (2002) study innovation through learning by doing.

While the above-mentioned papers study innovation with cost-efficiency as the purpose, Poudineh et al. (2020) study how to incentivize innovation with decarbonization as the goal. They study regulatory models of electricity network utilities and find that when there is a difference in the risk profile of cost-efficiency and innovation, different incentive schemes should be used in order to account for the additional level of risk associated with innovation. Since the regulator cannot observe the firm's effort level, there is an issue of moral hazard as described previously, and the remuneration of the firm must be linked to firm performance instead of effort. Poudineh et al. (2020) state that the regulator should distinguish between early, risky stages of innovation and later stages that might have the same risk profile as the normal activities conducted by the firm. In the earlier stages, the regulator can mitigate the risk by using an input-based regulatory mechanism where innovation costs and output are separated, meaning the innovation costs are transferred to the consumers. In the later stages, the regulator can instead use an output-based regulatory mechanism where a cost reduction from the innovation is shared with the firm. This latter incentive corresponds with the findings by Lewis and Yildirim (2002).

Rong et al. (2022) describe how markets without environmental regulation lack incentives to develop and adopt so-called green or environmental technologies and how this is primarily due to incentive incompatibility and information asymmetry. Taking these two factors into account, they analyse how a social welfare-minded regulator, regulating a profit-maximizing firm, should design a policy to motivate the development and adoption of green technologies. The asymmetric information problem is both an issue of moral hazard since the regulator cannot observe the firm's efforts and an issue of adverse selection since the firm can choose to conceal the arrival of the technology from the regulator in order to avoid adoption costs. Rong et al. (2022) assume that the regulator can commit to a long-term policy. Then, they find the optimal regulatory policy to be one where a so-called report subsidy is paid to the firm when the firm reports that its technology is ready. The report subsidy declines over time and induces the firm to exert maximal effort until some effort deadline, minimal effort hereafter, and to report the technology as soon as it has been invented. They also incorporate a termination deadline after which the current technology expires, no matter if the new technology is ready or not. The aim of this deadline is to serve as a threat that induces the firm to act in the interest of the regulator. Altogether, this policy for inducing innovation in green technology proposed by Rong et al. (2022) is somewhat different from the mechanism suggested by Poudineh et al. (2020).

2.3 Evolutionary Game Theory and Environmental Regulation

Evolutionary game theory has increasingly been used for environmental policymaking. This has been examined by Faber and Frenken (2009) who conduct a review of the academic literature that employs evolutionary modelling in environmental studies. They find that applying evolutionary simulation tools for assessing environmental policies provides promising opportunities for policymakers and social scientists amongst others. Also in recent years, a number of studies have used evolutionary game theory for examining the strategic interactions between different groups of players with various aspects of environmental regulation or adoption of green technologies being the area of interest. The rest of this section will present some of these.

Encarnação et al. (2018) use evolutionary game theory for investigating the strategic interactions of governments, companies and consumers in relation to the adoption of electric vehicles. Their aim is to escape the so-called lock-in state which hinders the adoption of electric vehicles due to the current prevalence of internal combustion engine vehicles, and so, they study an incentive mechanism for assuring cooperation of all three populations. The modelling framework of Encarnação et al. (2018) is that each population can either choose to cooperate, meaning they are in favour of electric vehicles, or to maintain the status quo. The current status quo is a widespread dominance of internal combustion engine vehicles. By studying the evolutionary dynamics, they find that in order to escape the lock-in state where all three populations maintain the status quo and to achieve the aim of full adoption of electric vehicles, intervention from the public sector is required regardless of the initial actions taken by the other two populations. When the cooperation of the public sector has been ensured, incentive mechanisms can be implemented in order to get the two remaining populations to cooperate as well.

Tang et al. (2021) study the interactions of local governments in China and users of distributed photovoltaic systems. Unlike the majority of the research using evolutionary game theory for studying environmental regulation issues, they combine the evolutionary game model with empirical analysis to be able to both study the quantitative relationship between the variables of the model, which is an advantage of empirical analysis, and study strategy evolution while taking individual rationality into account, which can be done using game theory. They wish to examine how economic development and the cost of distributed photovoltaic systems affect subsidy strategies with the aim of being able to promote the development of distributed photovoltaic systems. In order to do this, first, they set up an evolutionary game model for studying the strategic interactions between local governments and users of distributed photovoltaic systems. Afterwards, they test the conclusions of the evolutionary game analysis using panel models. They find that the effect of subsidies is restricted by regional economic development (Tang et al., 2021).

Chong and Sun (2020), Jiang et al. (2019) and Sheng et al. (2020) set up a tripartite evolutionary game like Encarnação et al. (2018), but with the central government, local governments and polluting enterprises in China being the three groups of stakeholders and environmental regulation in China being the area of interest. They give a thorough review of applications of evolutionary game theory in environmental regulation. Jiang et al. (2019) point out that studies on the strategic interactions of multiple actors and their impact on regulatory and market outcomes are scarce, while Chong and Sun (2020) describe how they fill a gap in the research since a number of these applications study the game between one or two of these groups of stakeholders while the research on the interactions of all three groups is moderate. The examination of the strategic interactions amongst all three groups when studying the effective implementation of environmental regulation is interesting since the local governments both are responsible for implementing local environmental regulation policies and for securing economic growth (Jiang et al., 2019).

The aim of Chong and Sun (2020) is to examine the policy tools which the central government can use to encourage the local governments and polluting enterprises to implement environmental regulation and reduce emissions. Contrary to Encarnação et al. (2018) who only studied how to develop a mechanism which ensured the cooperation of all three populations, Chong and Sun (2020) conduct a stability analysis of all equilibrium points. Hereafter, they conduct a numerical simulation analysis in order to examine the effect of the parameters on the six equilibrium points where each group of stakeholders adopt a pure strategy that can become evolutionary stable states. They find that the initial parameters only have an effect on the rate of convergence to the evolutionary stable state, but not on the evolutionary results, and after conducting the stability analysis and numerical simulations, they find that the ideal evolutionary stable state is the state where the polluting enterprises reduce emissions, the local governments perform their duties and the central government does not inspect, meaning it decentralizes its power. Eventually, they propose a number of policy changes for improving environmental regulation (Chong & Sun, 2020).

Jiang et al. (2019) seek to study the impact of changes in the strategic behaviour among the different stakeholders. They do this by examining the impact of the initial position of polluting enterprises on the local governments' convergence to the ideal state which they define as the state with full central enforcement, local implementation and corporate mitigation, holding the behaviour of the central government constant. Then, they study the impact of the initial position of local governments on the central government's convergence to the ideal state, holding the behaviour of the polluting enterprises constant. By doing so, they show a great degree of interdependence among the agents. In addition to this, they perform numerical simulations in order to examine how specific conditions such as costs and benefits influence the convergence towards the ideal state for all three parties and find that the levels of enforcement supervision and fines influence the strategic choice of the central government.

Sheng et al. (2020) use the tripartite evolutionary game model for exploring incentive-compatible environmental regulation policies. As Chong and Sun (2020) and Jiang et al. (2019), they also conduct numerical simulations to study the effect of different parameters on the evolutionary stable strategies. They find that supervision and punishment from the central government are essential for implementing environmental regulation policies. Furthermore, they conclude that the willingness of the central government to implement supervision to a high degree depends on the ratio of supervision costs and penalties (Sheng et al., 2020).

Guo et al. (2021) and Yang et al. (2021) study a different angle of environmental regulation in China than the one presented above. Both of these papers study tripartite games with the aim of exploring how to encourage green innovation. The three groups of stakeholders in the paper by Guo et al. (2021) are government departments, green technology R&D institutions and green technology application enterprises. They seek to fill a gap in the academic literature by both studying the generation of new green technology and the improvement and upgrading of existing green technology. Just as Sheng et al. (2020), they also find the strategic choice made by the government to be essential for ensuring cooperation from the two remaining parties. They conclude that it is more beneficial for R&D institutions to conduct green technology R&D the greater the government's punishment and support is. Furthermore, they show that a direct relationship between the government and green technology application enterprises is necessary for inducing the enterprises to cooperate. Vice versa, they also find that cooperation from green technology R&D institutions and green technology application enterprises increases the government's support for green technology R&D (Guo et al., 2021).

Yang et al. (2021) set up an evolutionary game with the aim of studying possible conflicts of interests between local governments, university groups and industry groups in a green innovation ecosystem. They find that the industry groups and university groups will eventually either evolve into a state where both groups choose collaborative innovation or where both groups choose betrayal alliance. In addition to this, they show that if environmental regulations involving innovation subsidies and penalty costs from the government are introduced, it is more likely that the university and industry groups will choose collaborative innovation.

2.4 Contribution to the Literature

It is evident from sections 2.1, 2.2 and 2.3 that a good deal of research has been conducted on topics related to regulating monopolies, inducing innovation in regulated monopolies and applying evolutionary game theory for studying environmental regulation. However, to the best of my knowledge, no one has yet used evolutionary game theory with the purpose of investigating how to encourage innovation in energy networks. Also, research using evolutionary game theory in relation to the green transition outside China is scarce. Thus, through this thesis, I also extend the field of research by studying a case of green transition in the EU.

Chapter 3

Background

The objective of this section is to give an outline of the internal energy market in the EU and its evolvement into how it is structured today. In conjunction with this, the most important actors, rules and regulations will be presented. Lastly, the implications of the European Green Deal on the (regulation of the) internal energy market will be explained. As seen from the research question presented in chapter 1, the aim of this thesis is to investigate how to encourage energy networks, by which, throughout this thesis, is meant transmission system operators, to increase innovation with the goal of decarbonizing the energy sector. For this reason, the main focus of this section will be on the actors and regulations which are relevant for examining this problem.

3.1 The Internal Energy Market and its Surrounding Actors

The liberalisation of the European energy sector began in the 1990s. Before then, the energy markets were mainly controlled by monopolies that both monitored generation, transmission, distribution and retail supply. This resulted in unreasonably high energy prices. Through three energy packages containing a number of Directives and Regulations issued by the Commission, the internal energy markets in the EU were liberalised and integrated (Florence School of Regulation, 2020). The point of giving rise to a competitive and more integrated energy market was to ensure an affordable and reliable supply of energy for all citizens (European Commission, n.d.-b). As part of the liberalisation, the four formerly vertically integrated segments were vertically unbundled (Jamasb & Pollitt, 2005). The aim of this was to separate the segments that could be opened for competition from the natural monopoly activities. Thus, the generation and retail supply segments were made open for competition, while each Member State was required to create an independent National Regulatory Authority, hereafter referred to as the regulators, to regulate the monopoly activities of transmission and distribution networks (Florence School of Regulation, 2020; Jamasb & Pollitt, 2005). The role of the regulators and energy networks will be elaborated on in section 4.2.1.

With the third energy package in 2009, the European Union Agency for the Cooperation of Energy Regulators, commonly referred to as ACER, and the European Network for Transmission System Operators for Electricity and Gas, ENTSO-E and ENTSOG in short, were established (European

Commission, n.d.-g). As the name implies, one of the roles of ACER is to ensure cooperation between the regulators. By doing so among other things, ACER supports the integration of the national energy markets in the EU, monitors the smooth functioning and transparency of the internal market, including retail prices and consumer rights, and advises the institutions of the EU on trans-European issues related to energy infrastructure (ACER, n.d.-b). As part of this, ACER decides on cross-border issues if the regulators have a disagreement (European Commission, n.d.-g). ACER also performs the duty of monitoring the work of the ENTSOs and ensuring that their EU-wide Ten Year Network Development Plans, which are known as TYNDPs in short and will be described below, are aligned with the priorities set by the Commission. ACER is independent of the Commission, national governments and energy companies.

The ENTSOs are the networks through which the energy networks work together. This is necessary in order to ensure the optimal management of the networks in the EU across the borders of the Member States. One of the responsibilities of the ENTSOs is to identify investment gaps and coordinate the planning of network investments. As part of this, they are responsible for publishing the above-mentioned TYNPDs for electricity and gas, which are non-binding Union-wide plans that build on national development plans prepared by the energy networks (ACER, n.d.-c, n.d.-d; European Commission, n.d.-g). The TYNDPs also provide the basis for selecting the so-called Projects of Common Interest, abbreviated as PCIs, that were introduced with the TEN-E Regulation since the PCIs are chosen from the most recent TYNDP. The idea behind the PCIs will be outlined below together with the TEN-E Regulation.

The focus of the TEN-E Regulation, which is short for the Trans-European Networks for Energy Regulation, is to link the energy infrastructure of the Member States of the EU (European Commission, n.d.-h). Among other things, this involves the identification of nine priority corridors and three priority thematic areas. Within these, the Commission supports the collaboration in developing better connected energy networks. The aforementioned PCIs are energy infrastructure projects linked to the priority corridors or the thematic areas (European Commission, n.d.-f). The investment costs of PCIs are split through cross-border cost allocation which ACER decides on in case the involved regulators are not able to reach an agreement, as mentioned above (ACER, n.d.-a). In addition to that, PCIs can get funding from the Connecting Europe Facility (European Commission, n.d.-e).

3.2 The European Green Deal and the Internal Energy Market

As mentioned in chapter 1, the Commission presented the European Green Deal in December 2019 (European Commission, n.d.-a). In July 2021, the European Climate Law entered into force (European Commission, n.d.-d). With this, the target of net zero greenhouse gas emissions by 2050 of the European Green Deal was made legally binding. This involves that the EU institutions and the Member States are required to take the necessary measures at both EU and national levels in order to meet this target. Since the energy sector is a large emitter, decarbonizing the energy system is crucial in order to reach the goal of climate neutrality by 2050 (European Commission, n.d.-c). The part of the European Green Deal that concerns a clean energy transition focuses on three key principles. One of these is to develop a fully integrated, interconnected and digitalized energy market (European Commission, n.d.-c). This relates to the TEN-E Regulation as described above. In the wake of the adoption of the European Green Deal, a revision of the TEN-E Regulation with the purpose of making it compatible with the European Green Deal has begun (European Commission, n.d.-h). Amongst other things, this includes promoting energy system integration and continuously linking the energy infrastructure within the EU. The significance of the TEN-E Regulation for achieving the decarbonization goals of the European Green Deal will be elaborated in section 4.2.1.1.

Chapter 4

Research Design

As described in chapter 1, the aim of this thesis is to investigate how to encourage energy networks in the EU to invest in innovation with decarbonization goals. This is done by setting up a tripartite evolutionary game with the Commission, the regulators and the energy networks in the EU being the three groups of players. In section 4.1, the methodology of evolutionary game theory is presented. The game is set up in section 4.2, and in section 4.3 it is described how numerical simulations of the game are conducted.

4.1 Evolutionary Game Theory

Evolutionary game theory falls under the category of non-cooperative game theory (Weibull, 1995), but where traditional game theory builds on the strong assumption of all players being fully rational, evolutionary game theory works with the somewhat less strong assumption of bounded rationality of players (Chong & Sun, 2020). In evolutionary game theory, it is assumed that the game is repeated and that one randomly drawn player from each population, playing some pure strategy h, plays the game each period (Weibull, 1995). Another important assumption of evolutionary game theory is that the players are assumed to be able to learn over time and adjust their strategies accordingly (Yang et al., 2021). Following standard replicator dynamics, the growth rate of the strategy h can be expressed as the excess expected payoffs of choosing this strategy over the average payoffs in the population. Hence, the change in the proportion of the population playing this strategy, or the change in the probability that a randomly drawn player from the population plays this strategy, over time can be expressed by the replicator dynamics equation (Weibull, 1995):

$$F(x_h) = \frac{dx_h}{dt} = x_h \left[u_h\left(x\right) - u\left(x\right)\right] \tag{4.1}$$

where x_h is the proportion of the population playing strategy h, or the probability that a randomly drawn player from the population plays strategy h, while $[u_h\left(x\right) - u\left(x\right)]$ is the excess expected payoffs of choosing this strategy over the average payoffs in the population. This implies that if the payoffs from a strategy h exceeds the average payoffs in the population, then the proportion x_h of the population playing this strategy will grow over time.

If the replicator dynamics equation, $F(x_h)$, reaches a stable state in iteration, then strategy h is an evolutionary stable strategy, and the state is an evolutionary stable state, abbreviated as ESS (Shan & Yang, 2019). A necessary and sufficient condition for determining whether a derived equilibrium point is asymptotically stable is that all eigenvalues of the Jacobian matrix for the equilibrium point must be negative (Shan & Yang, 2019). Asymptotic stability in this sense means that sufficiently small shocks to the equilibrium results in a movement back to the ESS (Weibull, 1995). The Jacobian matrix for a tripartite game can be set up as follows, following Friedman (1998):

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} \tag{4.2}$$

Then, the eigenvalues of the matrix are the solutions λ_1, λ_2 and λ_3 to the equation $|J - \lambda\mathbf{I}| = 0$, where $\mathbf{I}$ is the identity matrix (Friedman, 1998). If one or more of the eigenvalues are not negative, then the examined point is not an ESS but a source or a saddle point, meaning it is not stable (Chong & Sun, 2020). All ESSs are Nash equilibria, but the reverse is not the case. For a state to be an ESS, one of two conditions must be satisfied. The first condition is that each player's expected payoffs in this state is strictly better than the payoffs they would get from choosing a different strategy, assuming the strategies of the other players are constant. This condition is sometimes referred to as a strict Nash equilibrium. The second condition is that each player's expected payoffs in this state is the same as the payoffs they would get from choosing a different strategy, assuming the strategies of the other players are constant, *and* that the expected payoffs from choosing this strategy in another state would be strictly better than choosing any other strategy (Friedman, 1998). By comparison, a state is a Nash equilibrium if the expected payoffs each player gets in this state is weakly better than if they chose a different strategy, assuming the strategies of the remaining players do not change.

4.2 Setting up the Game

In this section, the three groups of players, their possible strategies and their resulting payoffs will be presented. As will be evident from section 5.2, the Commission having the power to penalize national regulators if they do not cooperate and itself being subject to a penalty if it does not comply with its own regulations are essential assumptions for getting the three populations to cooperate. In sections 4.2.1.1 and 4.2.2, arguments for why these assumptions can be presumed to hold will be posed, but since the assumptions can also be argued to be quite strict, four different cases of the game will be examined. Case 1 leaves out these additional assumptions. In case 2, it is assumed that the Commission has the power to penalize the regulators. In case 3, it is assumed that the Commission is subject to a penalty if it does not comply with its own regulations. Case 4 incorporates both of these additional assumptions. The possible strategies of the three groups of players, including the distinction between the four cases, are introduced in section 4.2.1. Moreover, the strategies are summarized in figure 4.1, however, without the distinction between the four cases while the payoffs for the players in the different outcomes of the game are presented in section 4.2.2. Section 4.2.3 sums up the assumptions of the game.

4.2.1 The Players and their Strategies

4.2.1.1 The Commission

The first player of the tripartite evolutionary game is the Commission. The Commission is behind the European Green Deal and strives to reach the decarbonization goals of this. As stated in section 3.2, developing a fully integrated energy market is part of the solution to decarbonizing the energy system. There is a broad consensus in the academic literature on the importance of increasing innovation in the energy sector, including in energy networks, in order to achieve this (Jamasb et al., 2020). Importantly in relation to this, the Commission is responsible for the TEN-E Regulation, as presented in section 3.1. According to Schittekatte et al. (2021), this regulation needs to be revised with one of the objectives being to promote the development of innovative technologies in order to decarbonize the trans-European networks for energy. As part of this, they recommend a revision of the PCI list to make it more up-to-date with meeting the decarbonization goals of the European Green Deal. Furthermore, they suggest interpreting cross-border relevance in a broader way, since some new infrastructure projects that enable integration of the energy sector can be seen to compete with or complement traditional cross-border infrastructure, although these new projects do not geographically have a cross-border footprint.

Another point made by Schittekatte et al. (2021) is that energy infrastructure projects typically involve high private costs early in the innovation process, whereas social and environmental costs and benefits are accrued over a longer time horizon. For this reason, a so-called social discount rate and a sufficiently long time horizon should be used when conducting cost-benefit analyses as part of working out the TYNDP. In this way, future social and environmental costs and benefits will be valued higher. They also propose an integration of the TYNDPs for gas and electricity which should then be worked out jointly by the two ENTSOs. Moreover, they pose that the only award criterion linked directly to CEF-E funding , i.e. funding from the Connecting Europe Facility, which was presented in section 3.1, to energy projects, should be affordability, meaning the net welfare benefits from a project are positive, but the energy consumers cannot afford to pay for it (Schittekatte et al., 2021).

Haffner et al. (2019) also investigate whether a change in EU regulation would make sense in order to increase innovation in energy networks. They find that it may be an idea to impose a requirement on energy networks to consider innovative solutions and to perform social cost-benefit analyses for larger projects that are not part of the TYNDPs. However, at first, they suggest merely working out a recommendation for both of these points, meaning there would be no consequence for neither regulators nor energy networks if the recommendations are not followed. For this reason, I will not take this into consideration in the game since converting it into payoffs is not straightforward. Based on this and the paragraphs above, in case 1 and case 3 of the game, the Commission can either choose a cooperative strategy which implies it will pass new legislation in order to induce innovation with decarbonization objectives, or it can choose a non-cooperative strategy which means it will not change the current legislation. In case 2 and case 4, it is further assumed that if the Commission chooses its cooperation strategy as described before, it also incorporates into the legislation that the regulators must change their regulatory practice to one that induces innovation. If the regulators do not do so, the Commission imposes a penalty on them. It has been seen in previous cases where regulators have not followed EU legislation that the Commission has followed up with infringement proceedings (Haffner et al., 2019). Based on this, it appears to be a reasonable assumption.

4.2.1.2 Regulators

The next players are the regulators of all the Member States, coordinated by ACER as described in section 3.1. As was also mentioned in the aforementioned section, one of the roles of the regulators is to regulate the natural monopoly activities of the energy networks. The main objective of the regulators is to reduce the asymmetry of information, as discussed in section 2.1, and to protect the consumers by avoiding that the regulated companies, i.e. the energy networks, set too high prices (Directive (EU) 2019/944, 2019). At present, the majority of tariff methodologies used by the regulators as financing mechanisms either fall into the category of cost-based regulation, incentive-based regulation, a combination of these two or state budgetary control over state-owned bodies (Haffner et al., 2019). Cost-based regulation guarantees the firm their cost of production plus a pre-defined rate of return on capital in the case of rate of return regulation or their cost of production plus a pre-defined profit margin in the case of cost-plus regulation (Haffner et al., 2019; Jamasb et al., 2020). Thus, cost-based regulation does not provide incentives for innovation and might lead to the firm misreporting its costs. On the other hand, as implied by the name, incentive-based regulation provides the firm with incentives for improving efficiency by allowing it to get a share of the extra profits from over-fulfilling the regulator's goal which has historically typically been to improve cost-efficiency in the short term.

As seen from section 2.2, the academic literature deals with different aspects of the regulation of innovation in monopolies. While a lot of the literature focuses on innovation with cost-efficiency at aim, Poudineh et al. (2020) suggest incentive schemes that deal with the moral hazard issue of not being able to observe the firm's effort level for inducing innovation with decarbonization as the goal. As also mentioned in section 2.2, they suggest using an input-based mechanism for regulating the earlier and more risky innovation stages and an output-based mechanism for the later innovation stages that might have the same risk profile as the normal activities of the firm. By using an output-based mechanism, the energy networks can be remunerated based on their performance rather than effort which takes the moral hazard issue presented in sections 2.1 and 2.2 into account. Jamasb et al. (2020) also state the need for moving away from regulatory mechanisms focused on improving cost-efficiency in the short term and instead incorporate one or more mechanisms that focus on long-term goals and consider the higher risk profile of innovations in energy networks. In connection with this, they also suggest using an input-based regulatory mechanism for incentivizing innovation where costs are incurred today while benefits emerge in the long term and are uncertain. Furthermore, they propose combining the input-based mechanism with an output-based mechanism which lets the firm benefit from an improvement of outcomes. All in all, this corresponds to the suggestions made by Poudineh et al. (2020). In addition to that, following Lewis and Yildirim (2002), sharing the surplus from innovation might benefit both parties. Haffner et al. (2019) find regulatory uncertainty to be a potential barrier to invest. As seen from section 2.2, this is supported by Lim and Yurukoglu (2018) who find a potential solution to be to set the rate-of-return policy so that more weight is placed on the profits of the firm than on consumer surplus. Hence, this also suggests that sharing the surplus from innovation with the energy networks might mitigate the negative effect of regulatory uncertainty on investments in innovation.

As with the Commission, the regulators can also choose either a cooperative or a non-cooperative strategy. On the basis of the paragraphs above, the cooperative strategy involves changing to a combination of input-based and output-based regulatory mechanisms in order to incentivize investment in innovation with decarbonization as the goal. On the basis of the research findings discussed above, this combination of mechanisms is thought to overcome more of the reasons presented by Jamasb and Pollitt (2008) for the decline in R&D spending in the energy sector following the liberalisation such as increased uncertainty and pressure for short-term profitability, as presented in section 2.2. Alternatively, they can choose the non-cooperative strategy of continuing to use a regulatory mechanism which is cost-based or focuses on improving cost-efficiency.

4.2.1.3 Energy networks

The third and last group of players are the energy networks in the EU. As stated in section 2.2, there has been a significant decline in R&D spending in the energy sector following the liberalisation of the sector in the 1990s. One of the legal obligations of the energy networks is to operate, maintain and develop the transmission networks (Haffner et al., 2019). Also, it is the responsibility of the energy networks to work together with other energy networks on cross-border and integrated market issues. Since one of the key principles of the European Green Deal is to develop a fully integrated, interconnected and digitalised energy market, as explained in section 3.2, the energy networks play an important role in the decarbonization of the sector.

As mentioned in section 3.1, the energy networks work together through the ENTSOs who amongst other things identify investment gaps and coordinate the planning of network investments. Although it is evident from sections 4.2.1.1 and 4.2.1.2 that both the Commission and the regulators are important players when wanting to increase innovation in energy networks, the energy networks themselves constitute the most important group of stakeholders since the main objective of the evolutionary game analysis is to give an answer to how they can be encouraged to invest in innovation with decarbonization goals, as stated in the research question posed in chapter 1. Following this, the cooperative strategy of the energy networks is, in accordance with the aforementioned research question, to invest in innovation with decarbonization as the goal whereas the non-cooperative strategy is to not invest.

The strategies of the three groups of players are summed up in figure 4.1.

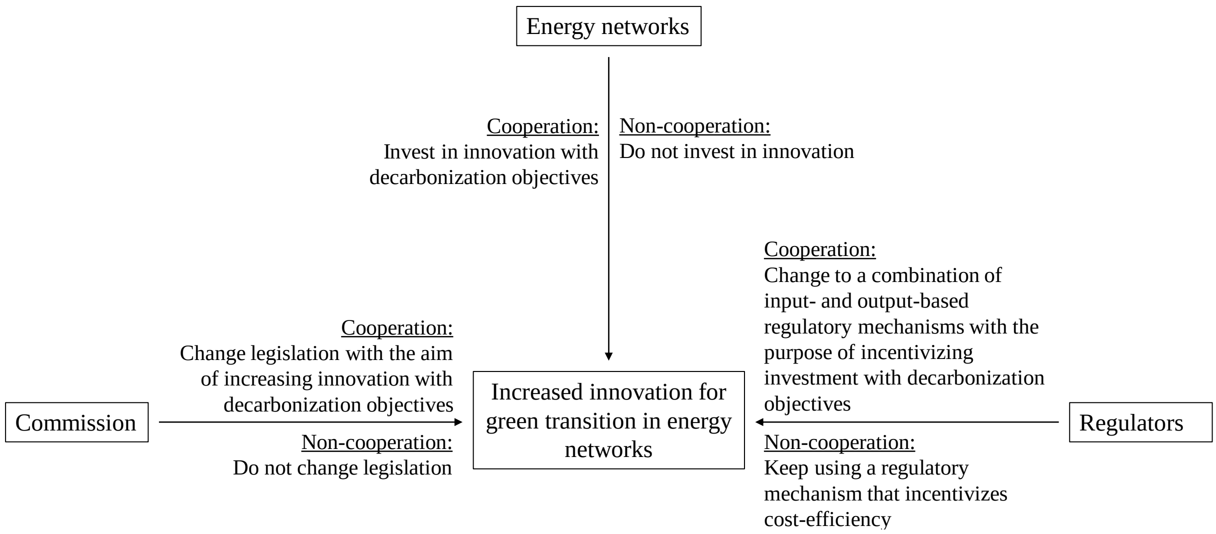

Figure 4.1: Strategies of the game.

4.2.2 Payoffs

As mentioned in section 4.2.1.1, the cooperative strategy of the Commission is to pass new legislation which among other things involves revising the TEN-E regulation in order to make investment in innovation with decarbonization objectives more favourable. The alternative strategy that the Commission can choose is to not change the current legislation. In case 1 and case 3, the strategy chosen by the Commission has no direct effect on the payoffs of the regulators, but in case 2 and case 4, the regulators will receive a negative payoff p, corresponding to the penalty imposed by the Commission, if they choose their non-cooperative strategy while the Commission chooses its cooperative strategy. Imposing a penalty on the regulators is also assumed to involve a cost c_2 for the Commission.

The payoffs of the energy networks are also affected by the strategy chosen by the Commission if they choose their cooperative strategy of investing in innovation. If the Commission passes the new legislation, it will be more favourable to invest in innovative decarbonization projects. I assume the energy networks in this case, if they choose to invest in innovation, will receive an expected amount $\alpha_1 \times F$ in external funding, such as CEF-E funding. If the Commission does not pass new legislation, the energy networks will only receive an expected amount $\alpha_2 \times F$ with $\alpha_1 > \alpha_2$, corresponding to the amount of external funding today. F is the average external funding for a project, while α_1 and α_2 can be thought of as the percentage of the average external funding that the energy networks receive or the probability of getting the average external funding. Since it is assumed to be the average funding across energy networks, funding from other energy networks through cross-border cost allocation average out and is thus not considered here. If the energy networks choose to invest in innovation with decarbonization goals, this will result in positive environmental benefits E_1 for the Commission which is pushing the European Green Deal. On the other hand, there will be an environmental cost E_2 for the Commission if the energy networks do not choose to invest in innovation.

Since the Commission pushes the TEN-E regulation and the TYNDPS and hence also has a stake when it comes to funding such as CEF-E funding, the external funding the energy networks receive in case they choose to invest in innovation is assumed to be deduced from the Commission's payoffs. Furthermore, the strategy which is chosen by the Commission also has a direct effect on its own payoffs. If it chooses its cooperative strategy, there is a cost c_1 associated with all the work involved in the process of changing regulation. In case 3 and case 4, there is also a negative payoff for the Commission associated with choosing its non-cooperative strategy of not changing regulation. As a consequence of the European Climate Law, the Commission is bound to take the necessary measures of meeting the legally binding target of net zero greenhouse gas emissions by 2050, as mentioned in section 3.2 (European Commission, n.d.-d). If it does not change its legislation with the aim of inducing innovation with decarbonization objectives, this is thought to contradict the European Climate Law, and in case 3 and case 4 this is assumed to result in a penalty of size q on the Commission. Who is responsible for imposing this penalty and choosing the size of it and if it is exogenously determined in this model can be a matter of debate and will be discussed in sections 4.3 and 6.1.

The effect of the strategy chosen by the regulators on the payoffs of the energy networks is clear. As seen from section 4.2.1.2, the cooperative strategy that can be chosen by the regulators involves changing to a combination of an input-based and output-based mechanism which is supposed to incentivize investment in innovation with decarbonization goals. For the sake of calculating payoffs, it is assumed that the input-based part of the mechanism involves that the expenses associated with the innovation, i.e. the investment costs I, are directly transferred to the consumers, represented by the regulators. At the same time, it is assumed that a given innovation leads to a cost reduction s of which a share β goes to the energy networks as a result of the output-based mechanism. The remaining share, $1 - \beta$, goes to the regulators who, as mentioned previously, represent the consumers. If the regulators instead choose the non-cooperative strategy of not changing their regulatory mechanism to one which induces innovation, then it is assumed that the entire cost reduction s in the case that energy networks choose to invest goes to the regulators. In this case, the energy networks themselves will pay the cost I associated with investing in innovation. The regulators get a cost c_3 from changing their regulatory practice.

A description of the different parameters is summarized in table 4.1. Then, based on the paragraphs above, we can set up eight payoff functions for each of the three groups of players in each of the four cases. In table 4.2, the payoffs of the three groups of players in each state of the world are summarized. Furthermore, the payoff functions corresponding to these eight possible outcomes of the game are specified for each of the four cases of the game in tables 4.3, 4.4 and 4.5.

4.2.3 Assumptions

Based on sections 4.1 and 4.2.1, I set up the following assumptions for the game (Liu et al., 2021):

Symbol	Description	Value range
E_1	Environmental benefits for the Commission when energy networks invest in innovation with decarbonization goals	≥ 0
E_2	Environmental costs for the Commission when energy networks do not invest in innovation with decarbonization goals	≥ 0
F	Average external funding for innovative projects	≥ 0
α_1	Probability of receiving average external funding when the Commission changes regulation	$1 \geq \alpha_1 > \alpha_2 \geq 0$
α_2	Probability of receiving average external funding when the Commission does not change regulation	
c_1	Cost of changing regulation for the Commission	≥ 0
c_2	Cost of penalizing regulators for the Commission	
c_3	Cost of changing regulatory practice for regulators	≥ 0
I	Cost of investing in innovation with decarbonization goals	≥ 0
s	Cost reductions from innovation with decarbonization goals	≥ 0
β	Percentage of cost reductions given to energy networks if regulators change their regulatory practice	$1 \geq \beta \geq 0$
p	Penalty imposed on regulators if they do not change their regulatory practice and the Commission changes its legislation	≥ 0
q	Penalty imposed on the Commission if it does not change its legislation	≥ 0

Table 4.1: List of parameters in the game. Note that c_2 and p only pertain to case 2 and case 4, while q only pertains to case 3 and case 4.

Strategies (Commission, Regulators, Energy Networks)	Payoffs (Commission, Regulators, Energy Networks)
(C, C, C)	$(\pi_{EC-1}, \pi_{R-1}, \pi_{EN-1})$
(C, C, N)	$(\pi_{EC-2}, \pi_{R-2}, \pi_{EN-2})$
(C, N, C)	$(\pi_{EC-3}, \pi_{R-3}, \pi_{EN-3})$
(N, C, C)	$(\pi_{EC-4}, \pi_{R-4}, \pi_{EN-4})$
(C, N, N)	$(\pi_{EC-5}, \pi_{R-5}, \pi_{EN-5})$
(N, C, N)	$(\pi_{EC-6}, \pi_{R-6}, \pi_{EN-6})$
(N, N, C)	$(\pi_{EC-7}, \pi_{R-7}, \pi_{EN-7})$
(N, N, N)	$(\pi_{EC-8}, \pi_{R-8}, \pi_{EN-8})$

Table 4.2: Payoff matrix. C and N stands for cooperation and non-cooperation, respectively.

1. The Commission can either choose its cooperation strategy with probability x, $0 \leq x \leq 1$, or choose its non-cooperation strategy with probability $1 - x$.

2. The regulators can either choose their cooperation strategy with probability y, $0 \leq y \leq 1$, or choose their non-cooperation strategy with probability $1 - y$.

3. The energy networks can either choose their cooperation strategy with probability z, $0 \leq z \leq 1$, or choose their non-cooperation strategy with probability $1 - z$.

4. All players are boundedly rational.

5. All players can learn over time and adjust their strategies accordingly.

	Case 1 (π_{EC1})	Case 2 (π_{EC2})	Case 3 (π_{EC3})	Case 4 (π_{EC4})
π_{EC-1}	$E_1 - \alpha_1 F - c_1$	$E_1 - \alpha_1 F - c_1$	$E_1 - \alpha_1 F - c_1$	$E_1 - \alpha_1 F - c_1$
π_{EC-2}	$-E_2 - c_1$	$-E_2 - c_1$	$-E_2 - c_1$	$-E_2 - c_1$
π_{EC-3}	$E_1 - \alpha_1 F - c_1$	$E_1 - \alpha_1 F - c_1 - c_2$	$E_1 - \alpha_1 F - c_1$	$E_1 - \alpha_1 F - c_1 - c_2$
π_{EC-4}	$E_1 - \alpha_2 F$	$E_1 - \alpha_2 F$	$E_1 - \alpha_2 F - q$	$E_1 - \alpha_2 F - q$
π_{EC-5}	$-E_2 - c_1$	$-E_2 - c_1 - c_2$	$-E_2 - c_1$	$-E_2 - c_1 - c_2$
π_{EC-6}	$-E_2$	$-E_2$	$-E_2 - q$	$-E_2 - q$
π_{EC-7}	$E_1 - \alpha_2 F$	$E_1 - \alpha_2 F$	$E_1 - \alpha_2 F - q$	$E_1 - \alpha_2 F - q$
π_{EC-8}	$-E_2$	$-E_2$	$-E_2 - q$	$-E_2 - q$

Table 4.3: Payoffs for the Commission in the four different cases of the game.

	Case 1 (π_{R1})	Case 2 (π_{R2})	Case 3 (π_{R3})	Case 4 (π_{R4})
π_{R-1}	$(1-\beta)s - I - c_3$	$(1-\beta)\, s - I - c_3$	$(1-\beta)\, s - I - c_3$	$(1-\beta)\, s - I - c_3$
π_{R-2}	$-c_3$	$-c_3$	$-c_3$	$-c_3$
π_{R-3}	s	$s - p$	s	$s - p$
π_{R-4}	$(1-\beta)s - I - c_3$	$(1-\beta)\, s - I - c_3$	$(1-\beta)\, s - I - c_3$	$(1-\beta)\, s - I - c_3$
π_{R-5}	0	$-p$	0	$-p$
π_{R-6}	$-c_3$	$-c_3$	$-c_3$	$-c_3$
π_{R-7}	s	s	s	s
π_{R-8}	0	0	0	0

Table 4.4: Payoffs for the regulators in the four different cases of the game.

	Case 1 (π_{EN1})	Case 2 (π_{EN2})	Case 3 (π_{EN3})	Case 4 (π_{EN4})
π_{EN-1}	$\alpha_1 F + \beta s + I - I$	$\alpha_1 F + \beta s + I - I$	$\alpha_1 F + \beta s + I - I$	$\alpha_1 F + \beta s + I - I$
π_{EN-2}	0	0	0	0
π_{EN-3}	$\alpha_1 F - I$	$\alpha_1 F - I$	$\alpha_1 F - I$	$\alpha_1 F - I$
π_{EN-4}	$\alpha_2 F + \beta s + I - I$	$\alpha_2 F + \beta s + I - I$	$\alpha_2 F + \beta s + I - I$	$\alpha_2 F + \beta s + I - I$
π_{EN-5}	0	0	0	0
π_{EN-6}	0	0	0	0
π_{EN-7}	$\alpha_2 F - I$	$\alpha_2 F - I$	$\alpha_2 F - I$	$\alpha_2 F - I$
π_{EN-8}	0	0	0	0

Table 4.5: Payoffs for the energy networks in the four different cases of the game.

4.3 Numerical Simulations

Following the literature on evolutionary game theory (see, e.g., Chong and Sun, 2020, Liu et al., 2021, and Sheng et al., 2020), I conduct a number of numerical simulations in order to investigate the impact of a number of chosen parameters on the convergence to a stable state. As will be evident from section 5.2, the only equilibrium point in the four cases of the game that can be stable is the equilibrium in case 4 that involves the cooperation of all three groups of players. Hence, numerical simulations will only be conducted for this ESS. There is great uncertainty with several of the parameters, for example, costs of changing regulations, cost reductions from innovation, and how large a percentage of innovative projects in energy networks in the EU in total, not just of PCIs, are financed by CEF-E funding.

Due to this, the simulations are carried out for four different scenarios, following the procedure by Chong and Sun (2020).

The parameters E_1, E_2, F, α_2, c_1, c_2, c_3, I and s are assumed to be given, while α_1, β, p and q are assumed to be the result of the regulations implemented by the Commission and the regulatory practice chosen by the regulators in case these two groups of players choose their cooperation strategies, although it can be discussed who has to power to adjust the parameter q and if it is in fact exogenously determined in the model, as mentioned in section 4.2.2 and discussed in section 6.1. Then, the four scenarios are set up so that the parameters assumed to be given are chosen with different ratios between them while sensitivity analyses are conducted for the four remaining parameters in order to investigate the impact of a change in each of them on the convergence to the ESS. All parameters are chosen so that the boundaries derived in section 5.2 are met. In addition to the sensitivity analyses of the chosen parameters, sensitivity analyses are carried out to examine the impact of the initial values of x, y and z on the convergence rate to the ESS.

Chapter 5

Results and Analysis

This section presents the outcomes of the game introduced in section 4.2. In section 5.1, the replicator dynamics equations for each group of players in the four cases are derived. Using these, the equilibrium points of each case of the game are found in section 5.2, and the stability of all equilibrium points involving cooperation from the energy networks is examined. Finally, in section 5.3, numerical simulations are conducted for the only possible ESS of the game.

5.1 Replicator Dynamics Equations

In order to derive the possible ESSs, a system of replicator dynamics equations are set up and solved as described in section 4.1 for all four cases outlined in section 4.2. This first involves deriving the expected payoffs from cooperation and non-cooperation, respectively, for all three groups of players after which the replicator dynamics equations can be derived.

5.1.1 Case 1

Expected payoffs of the Commission if it chooses its cooperation strategy:

$$\begin{aligned}\pi_{EC1-C} &= y\big[z\big(\pi_{EC1-1}\big)+\big(1-z\big)\big(\pi_{EC1-2}\big)\big] \\ &\quad+\big(1-y\big)\big[z\big(\pi_{EC1-3}\big)+\big(1-z\big)\big(\pi_{EC1-5}\big)\big] \\ &= y\big[z\big(E_1-\alpha_1\ F-c_1\big)+\big(1-z\big)\big(-E_2-c_1\big)\big] \\ &\quad+\big(1-y\big)\big[z\big(E_1-\alpha_1 F-c_1\big)+\big(1-z\big)\big(-E_2-c_1\big)\big] \\ &= z\big(E_1+E_2-\alpha_1 F\big)-E_2-c_1\end{aligned} \tag{5.1}$$

Expected payoffs of the Commission from choosing its non-cooperation strategy:

$$\begin{aligned}\pi_{EC1-N} &= y\big[z\big(\pi_{EC1-4}\big)+\big(1-z\big)\big(\pi_{EC1-6}\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(\pi_{EC1-7}\big)+\big(1-z\big)\big(\pi_{EC1-8}\big)\big] \\ &= y\big[z\big(E_1-\alpha_2 F\big)+\big(1-z\big)\big(-E_2\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(E_1-\alpha_2 F\big)+\big(1-z\big)\big(-E_2\big)\big] \\ &= z\big(E_1+E_2-\alpha_2 F\big)-E_2\end{aligned} \tag{5.2}$$

Average expected payoffs of the Commission:

$$\begin{aligned}\bar{\pi}_{EC1} &= x\big(\pi_{EC1-C}\big)+\big(1-x\big)\big(\pi_{EC1-N}\big) \\ &= x\big[z\big(E_1+E_2-\alpha_1 F\big)-E_2-c_1\big] \\ &\quad + \big(1-x\big)\big[z\big(E_1+E_2-\alpha_2 F\big)-E_2\big] \\ &= z\big(E_1+E_2\big)-E_2-xc_1-zF\big[x\alpha_1+\big(1-x\big)\alpha_2\big]\end{aligned} \tag{5.3}$$

Expected payoffs of the regulators from choosing the cooperation strategy:

$$\begin{aligned}\pi_{R1-C} &= x\big[z\big(\pi_{R1-1}\big)+\big(1-z\big)\big(\pi_{R1-2}\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(\pi_{R1-4}\big)+\big(1-z\big)\big(\pi_{R1-6}\big)\big] \\ &= x\big[z\big((1-\beta)s-I-c_3\big)+\big(1-z\big)\big(-c_3\big)\big] \\ &\quad + \big(1-x\big)\big[z\big((1-\beta)s-I-c_3\big)+\big(1-z\big)\big(-c_3\big)\big] \\ &= z\big((1-\beta)s-I\big)-c_3\end{aligned} \tag{5.4}$$

Expected payoffs of the regulators from the non-cooperation strategy:

$$\begin{aligned}\pi_{R1-N} &= x\big[z\big(\pi_{R1-3}\big)+\big(1-z\big)\big(\pi_{R1-5}\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(\pi_{R1-7}\big)+\big(1-z\big)\big(\pi_{R1-8}\big)\big] \\ &= x\big[z\big(s\big)+\big(1-z\big)\big(0\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(s\big)+\big(1-z\big)\big(0\big)\big] \\ &= zs\end{aligned} \tag{5.5}$$

Average expected payoffs of the regulators:

$$\begin{aligned}\bar{\pi}_{R1} &= y\big(\pi_{R1-C}\big)+\big(1-y\big)\big(\pi_{R1-N}\big) \\ &= y\big[z\big((1-\beta)s-I\big)-c_3\big] \\ &\quad + \big(1-y\big)\big[zs\big] \\ &= zs-y\big[z\big(\beta s+I\big)+c_3\big]\end{aligned} \tag{5.6}$$

Expected payoffs of the energy networks from cooperation:

$$\begin{aligned}\pi_{EN1-C} &= x\big[y\big(\pi_{EN1-1}\big) + \big(1-y\big)\big(\pi_{EN1-3}\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN1-4}\big) + \big(1-y\big)\big(\pi_{EN1-7}\big)\big] \\ &= x\big[y\big(\alpha_1 F + \beta s\big) + \big(1-y\big)\big(\alpha_1 F - I\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\alpha_2 F + \beta s\big) + \big(1-y\big)\big(\alpha_2 F - I\big)\big] \\ &= y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\end{aligned} \tag{5.7}$$

Expected payoffs of the energy networks from non-cooperation:

$$\begin{aligned}\pi_{EN1-N} &= x\big[y\big(\pi_{EN1-2}\big) + \big(1-y\big)\big(\pi_{EN1-5}\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN1-6}\big) + \big(1-y\big)\big(\pi_{EN1-8}\big)\big] \\ &= x\big[y\big(0\big) + \big(1-y\big)\big(0\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(0\big) + \big(1-y\big)\big(0\big)\big] \\ &= 0\end{aligned} \tag{5.8}$$

Average expected payoffs of the energy networks:

$$\begin{aligned}\bar{\pi}_{EN1} &= z\big(\pi_{EN1-C}\big) + \big(1-z\big)\big(\pi_{EN1-N}\big) \\ &= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big] \\ &\quad + \big(1-z\big)\big[0\big] \\ &= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]\end{aligned} \tag{5.9}$$

Then, the replicator dynamics equations can be set up. By inserting equations 5.1 and 5.3, the replicator dynamics equation of the Commission can be written as:

$$\begin{aligned}F\big(x\big)_1 = \frac{dx}{dt} &= x\big(\pi_{EC1-C} - \bar{\pi}_{EC1}\big) \\ &= x\big[z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 \\ &\quad - \big(z\big(E_1 + E_2\big) - xc_1 - E_2 - zF\big[x\alpha_1 + \big(1-x\big)\alpha_2\big]\big)\big] \\ &= x\big(1-x\big)\big[zF\big(\alpha_2 - \alpha_1\big) - c_1\big]\end{aligned} \tag{5.10}$$

To derive the replicator dynamics equation of the regulators, equations 5.4 and 5.6 are inserted:

$$\begin{aligned}F\big(y\big)_1 = \frac{dy}{dt} &= y\big(\pi_{R1-C} - \bar{\pi}_{R1}\big) \\ &= y\big[z\big(\big(1-\beta\big)s - I\big) - c_3 - \big(zs - y\big[z\big(\beta s + I\big) + c_3\big]\big)\big] \\ &= y\big(1-y\big)\big[-z\big(\beta s + I\big) - c_3\big]\end{aligned} \tag{5.11}$$

The replicator dynamics equation of the energy networks can be derived as follows when inserting equations 5.7 and 5.9:

$$\begin{aligned} F\big(z\big)_1 &= \frac{dz}{dt} = z\big(\pi_{EN1-C} - \bar{\pi}_{EN1}\big) \\ &= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F \\ &\quad - \big(z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]\big)\big] \\ &= z\big(1-z\big)\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big] \end{aligned} \tag{5.12}$$

5.1.2 Case 2: The Commission can penalize the regulators

In this case where it is assumed that the Commission has the power to penalize the regulators in case they do not cooperate, the expected payoffs of the Commission from cooperation and of the regulators from non-cooperation changes compared to in case 1 while the expected payoffs of the Commission from non-cooperation and of the regulators from cooperation is the same as in case 1 (see tables 4.2, 4.3 and 4.4). The expected payoffs of the energy networks from both cooperation and non-cooperation is the same in all four cases, as can be seen from table 4.5. All calculations involved in deriving the replicator equations for the three groups of players in the four different cases can be seen from appendix A.

The expected payoffs of the Commission from cooperation when it has the power to penalize the regulators in case they do not cooperate is as follows:

$$\begin{aligned} \pi_{EC2-C} &= y\big[z\big(\pi_{EC2-1}\big) + \big(1-z\big)\big(\pi_{EC2-2}\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(\pi_{EC2-3}\big) + \big(1-z\big)\big(\pi_{EC2-5}\big)\big] \\ &= y\big[z\big(E_1 - \alpha_1 F - c_1\big) + \big(1-z\big)\big(-E_2 - c_1\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(E_1 - \alpha_1 F - c_1 - c_2\big) + \big(1-z\big)\big(-E_2 - c_1 - c_2\big)\big] \\ &= z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 - \big(1-y\big)c_2 \end{aligned} \tag{5.13}$$

The expected payoffs of the Commission from non-cooperation is the same as in equation 5.2:

$$\begin{aligned} \pi_{EC2-N} &= y\big[z\big(\pi_{EC2-4}\big) + \big(1-z\big)\big(\pi_{EC2-6}\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(\pi_{EC2-7}\big) + \big(1-z\big)\big(\pi_{EC2-8}\big)\big] \\ &= z\big(E_1 + E_2 - \alpha_2 F\big) - E_2 \end{aligned} \tag{5.14}$$

Then, the average expected payoffs of the Commission is:

$$\begin{aligned} \bar{\pi}_{EC2} &= x\big(\pi_{EC2-C}\big) + \big(1-x\big)\big(\pi_{EC2-N}\big) \\ &= x\big[z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 - \big(1-y\big)c_2\big] \\ &\quad + \big(1-x\big)\big[z\big(E_1 + E_2 - \alpha_2 F\big) - E_2\big] \\ &= z\big(E_1 + E_2\big) - E_2 - x\big[c_1 + \big(1-y\big)c_2\big] - zF\big(x\alpha_1 + \big(1-x\big)\alpha_2\big) \end{aligned} \tag{5.15}$$

The expected payoffs of the regulators from cooperation is the same as in 5.4:

$$\begin{aligned}\pi_{R2-C} &= x\big[z\big(\pi_{R2-1}\big) + \big(1-z\big)\big(\pi_{R2-2}\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(\pi_{R2-4}\big) + \big(1-z\big)\big(\pi_{R2-6}\big)\big] \\ &= z\big(\big(1-\beta\big)s - I\big) - c_3\end{aligned} \tag{5.16}$$

The expected payoffs of the regulators from non-cooperation is now:

$$\begin{aligned}\pi_{R2-N} &= x\big[z\big(\pi_{R2-3}\big) + \big(1-z\big)\big(\pi_{R2-5}\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(\pi_{R2-7}\big) + \big(1-z\big)\big(\pi_{R2-8}\big)\big] \\ &= x\big[z\big(s-p\big) + \big(1-z\big)\big(-p\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(s\big) + \big(1-z\big)\big(0\big)\big] \\ &= zs - xp\end{aligned} \tag{5.17}$$

Then, the average expected payoffs of the regulators in case 2 is:

$$\begin{aligned}\bar{\pi}_{R2} &= y\big(\pi_{R2-C}\big) + \big(1-y\big)\big(\pi_{R2-N}\big) \\ &= y\big[z\big(\big(1-\beta\big)s - I\big) - c_3\big] \\ &\quad + \big(1-y\big)\big[zs - xp\big] \\ &= zs - y\big[z\big(\beta s + I\big) + c_3\big] - \big(1-y\big)xp\end{aligned} \tag{5.18}$$

The expected payoffs of the energy networks from cooperation is the same as in equation 5.7:

$$\begin{aligned}\pi_{EN2-C} &= x\big[y\big(\pi_{EN2-1}\big) + \big(1-y\big)\big(\pi_{EN2-3}\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN2-4}\big) + \big(1-y\big)\big(\pi_{EN2-7}\big)\big] \\ &= y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\end{aligned} \tag{5.19}$$

The expected payoffs of the energy networks from non-cooperation is the same as in equation 5.8:

$$\begin{aligned}\pi_{EN2-N} &= x\big[y\big(\pi_{EN1-2}\big) + \big(1-y\big)\big(\pi_{EN2-5}\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN2-6}\big) + \big(1-y\big)\big(\pi_{EN2-8}\big)\big] \\ &= 0\end{aligned} \tag{5.20}$$

Thus, the average expected payoffs of the energy networks is the same as in equation 5.9:

$$\begin{aligned}\bar{\pi}_{EN2} &= z\big(\pi_{EN2-C}\big) + \big(1-z\big)\big(\pi_{EN2-N}\big) \\ &= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]\end{aligned} \tag{5.21}$$

Then, the replicator dynamics equations can be set up for case 2. The replicator dynamics equation of the Commission:

$$
\begin{aligned}
F(x)_2 = \frac{dx}{dt} &= x\big(\pi_{EC2-C} - \bar{\pi}_{EC2}\big) \\
&= x\big[z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 - \big(1-y\big)c_2 \\
&\quad - \big(z\big(E_1 + E_2\big) - E_2 - x\big[c_1 + \big(1-y\big)c_2\big] - zF\big(x\alpha_1 + \big(1-x\big)\alpha_2\big)\big)\big] \\
&= x\big(1-x\big)\big[zF\big(\alpha_2 - \alpha_1\big) - c_1 - \big(1-y\big)c_2\big]
\end{aligned}
\tag{5.22}
$$

The replicator dynamics equation of the regulators:

$$
\begin{aligned}
F(y)_2 = \frac{dy}{dt} &= y\big(\pi_{R2-C} - \bar{\pi}_{R2}\big) \\
&= y\big[z\big(\big(1-\beta\big)s - I\big) - c_3 - \big(zs - y\big[z\big(\beta s + I\big) + c_3\big] - \big(1-y\big)xp\big)\big] \\
&= y\big(1-y\big)\big[xp - z\big(\beta s + I\big) - c_3\big]
\end{aligned}
\tag{5.23}
$$

Also the replicator dynamics equation of the energy networks is the same for all four cases, meaning it corresponds to equation 5.12:

$$
\begin{aligned}
F(z)_2 = \frac{dz}{dt} &= z\big(\pi_{EN2-C} - \bar{\pi}_{EN2}\big) \\
&= z\big(1-z\big)\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]
\end{aligned}
\tag{5.24}
$$

5.1.3 Case 3: Penalty on the Commission for not cooperating

In this case where it is assumed that the Commission will be penalized for not cooperating, the expected payoffs of the Commission from cooperation is the same as in case 1 while the expected payoffs of the Commission from non-cooperation changes compared to the former two cases (see tables 4.2 and 4.3). The expected payoffs of the regulators from both cooperation and non-cooperation is the same as in case 1, as can be seen from table 4.4.

Thus, the expected payoffs of the Commission from cooperation is the same as in equation 5.1:

$$
\begin{aligned}
\pi_{EC3-C} &= y\big[z\big(\pi_{EC3-1}\big) + \big(1-z\big)\big(\pi_{EC3-2}\big)\big] \\
&\quad + \big(1-y\big)\big[z\big(\pi_{EC3-3}\big) + \big(1-z\big)\big(\pi_{EC3-5}\big)\big] \\
&= z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1
\end{aligned}
\tag{5.25}
$$

The expected payoffs of the Commission from non-cooperation is now:

$$
\begin{aligned}
\pi_{EC3-N} &= y\big[z\big(\pi_{EC3-4}\big) + \big(1-z\big)\big(\pi_{EC3-6}\big)\big] \\
&\quad + \big(1-y\big)\big[z\big(\pi_{EC3-7}\big) + \big(1-z\big)\big(\pi_{EC3-8}\big)\big] \\
&= y\big[z\big(E_1 - \alpha_2 F - q\big) + \big(1-z\big)\big(-E_2 - q\big)\big] \\
&\quad + \big(1-y\big)\big[z\big(E_1 - \alpha_2 F - q\big) + \big(1-z\big)\big(-E_2 - q\big)\big] \\
&= z\big(E_1 + E_2 - \alpha_2 F\big) - E_2 - q
\end{aligned}
\tag{5.26}
$$

Then, the average expected payoffs of the Commission is:

$$\begin{aligned}\bar{\pi}_{EC3} &= x\big(\pi_{EC3-C}\big) + \big(1-x\big)\big(\pi_{EC3-N}\big)\\ &= x\big[z\big(E_1+E_2-\alpha_1 F\big) - E_2 - c_1\big]\\ &\quad + \big(1-x\big)\big[z\big(E_1+E_2-\alpha_2 F\big) - E_2 - q\big]\\ &= z\big(E_1+E_2\big) - E_2 - \mathrm{xc}_1 - \big(1-x\big)q - zF\big(x\alpha_1 + \big(1-x\big)\alpha_2\big)\end{aligned} \tag{5.27}$$

The expected payoffs of the regulators from cooperation is the same as in equations 5.4 and 5.16:

$$\begin{aligned}\pi_{R3-C} &= x\big[z\big(\pi_{R3-1}\big) + \big(1-z\big)\big(\pi_{R3-2}\big)\big]\\ &\quad + \big(1-x\big)\big[z\big(\pi_{R3-4}\big) + \big(1-z\big)\big(\pi_{R3-6}\big)\big]\\ &= z\big(\big(1-\beta\big)s - I\big) - c_3\end{aligned} \tag{5.28}$$

The expected payoffs of the regulators from non-cooperation is the same as in equation 5.5:

$$\begin{aligned}\pi_{R3-N} &= x\big[z\big(\pi_{R3-3}\big) + \big(1-z\big)\big(\pi_{R3-5}\big)\big]\\ &\quad + \big(1-x\big)\big[z\big(\pi_{R3-7}\big) + \big(1-z\big)\big(\pi_{R3-8}\big)\big]\\ &= zs\end{aligned} \tag{5.29}$$

Consequently, the average expected payoffs of the regulators is the same as in equation 5.6:

$$\begin{aligned}\bar{\pi}_{R3} &= y\big(\pi_{R3-C}\big) + \big(1-y\big)\big(\pi_{R3-N}\big)\\ &= zs - y\big[z\big(\beta s + I\big) + c_3\big]\end{aligned} \tag{5.30}$$

The expected payoffs of the energy networks from cooperation is still as in equations 5.7 and 5.19:

$$\begin{aligned}\pi_{EN3-C} &= x\big[y\big(\pi_{EN3-1}\big) + \big(1-y\big)\big(\pi_{EN3-3}\big)\big]\\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN3-4}\big) + \big(1-y\big)\big(\pi_{EN3-7}\big)\big]\\ &= y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\end{aligned} \tag{5.31}$$

The expected payoffs of the energy networks from non-cooperation is the same as in equations 5.8 and 5.20:

$$\begin{aligned}\pi_{EN3-N} &= x\big[y\big(\pi_{EN3-2}\big) + \big(1-y\big)\big(\pi_{EN3-5}\big)\big]\\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN3-6}\big) + \big(1-y\big)\big(\pi_{EN3-8}\big)\big]\\ &= 0\end{aligned} \tag{5.32}$$

Average expected payoffs of the energy networks is as in equations 5.9 and 5.21:

$$\begin{aligned}\bar{\pi}_{EN3} &= z\big(\pi_{EN3-C}\big) + \big(1-z\big)\big(\pi_{EN3-N}\big)\\ &= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]\end{aligned} \tag{5.33}$$

Then, the replicator dynamics equations can be set up for case 3. Replicator dynamics equation for the cooperation strategy of the Commission:

$$\begin{aligned} F(x)_3 = \frac{dx}{dt} &= x\big(\pi_{EC3-C} - \bar{\pi}_{EC3}\big) \\ &= x\big[z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 \\ &\quad - \big(z\big(E_1 + E_2\big) - zF\big(x\alpha_1 + \big(1-x\big)\alpha_2\big) - E_2 - \mathrm{xc}_1 - \big(1-x\big)q\big)\big] \\ &= x\big(1-x\big)\big[zF\big(\alpha_2 - \alpha_1\big) - c_1 + q\big] \end{aligned} \tag{5.34}$$

The replicator dynamics equation for the cooperation strategy of the regulators is the same as in equation 5.11:

$$\begin{aligned} F(y)_3 = \frac{dy}{dt} &= y\big(\pi_{R3-C} - \bar{\pi}_{R3}\big) \\ &= y\big(1-y\big)\big[-z\big(\beta s + I\big) - c_3\big] \end{aligned} \tag{5.35}$$

The replicator dynamics equation for the cooperation strategy of the energy networks is the one also seen from equations 5.12 and 5.24:

$$\begin{aligned} F(z)_3 = \frac{dz}{dt} &= z\big(\pi_{EN3-C} - \bar{\pi}_{EN3}\big) \\ &= z\big(1-z\big)\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big] \end{aligned} \tag{5.36}$$

5.1.4 Case 4: The Commission can penalize the regulators and will be penalized for not cooperating

In case 4 where it is both assumed that the Commission has the power to penalize the regulators in case they do not cooperate and the Commission will be penalized for not cooperating, the expected payoffs of the Commission from cooperation is the same as in case 2 while the expected payoffs of the Commission from non-cooperation is the same as in case 3. The expected payoffs of the regulators from cooperation is the same as in the previous cases while the expected payoffs of the regulators from non-cooperation is the same as in case 2. The expected payoffs of the energy networks from both cooperation and non-cooperation is the same as in the previous cases. This can be seen from tables 4.2, 4.3, 4.4 and 4.5.

The expected payoffs of the Commission from cooperation corresponds to equation 5.13:

$$\begin{aligned} \pi_{EC4-C} &= y\big[z\big(\pi_{EC4-1}\big) + \big(1-z\big)\big(\pi_{EC4-2}\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(\pi_{EC4-3}\big) + \big(1-z\big)\big(\pi_{EC4-5}\big)\big] \\ &= z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 - \big(1-y\big)c_2 \end{aligned} \tag{5.37}$$

The expected payoffs of the Commission from non-cooperation is the same as in equation 5.26:

$$\begin{aligned}\pi_{EC4-N} &= y\big[z\big(\pi_{EC4-4}\big) + \big(1-z\big)\big(\pi_{EC4-6}\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(\pi_{EC4-7}\big) + \big(1-z\big)\big(\pi_{EC4-8}\big)\big] \\ &= z\big(E_1 + E_2 - \alpha_2 F\big) - E_2 - q\end{aligned} \tag{5.38}$$

Then, the average expected payoffs of the Commission is:

$$\begin{aligned}\bar{\pi}_{EC4} &= x\big(\pi_{EC4-C}\big) + \big(1-x\big)\big(\pi_{EC4-N}\big) \\ &= x\big[z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 - \big(1-y\big)c_2\big] \\ &\quad + \big(1-x\big)\big[z\big(E_1 + E_2 - \alpha_2 F\big) - E_2 - q\big] \\ &= z\big(E_1 + E_2\big) - E_2 - x\big(c_1 + \big(1-y\big)c_2\big) - \big(1-x\big)q - zF\big(x\alpha_1 + \big(1-x\big)\alpha_2\big)\end{aligned} \tag{5.39}$$

The expected payoffs of the regulators from cooperation is the same as in equations 5.4, 5.16 and 5.28:

$$\begin{aligned}\pi_{R4-C} &= x\big[z\big(\pi_{R4-1}\big) + \big(1-z\big)\big(\pi_{R4-2}\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(\pi_{R4-4}\big) + \big(1-z\big)\big(\pi_{R4-6}\big)\big] \\ &= z\big(\big(1-\beta\big)s - I\big) - c_3\end{aligned} \tag{5.40}$$

The expected payoffs of the regulators from non-cooperation is the same as in equation 5.17:

$$\begin{aligned}\pi_{R4-N} &= x\big[z\big(\pi_{R4-3}\big) + \big(1-z\big)\big(\pi_{R4-5}\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(\pi_{R4-7}\big) + \big(1-z\big)\big(\pi_{R4-8}\big)\big] \\ &= zs - xp\end{aligned} \tag{5.41}$$

Thus, the average expected payoffs of the regulators is the same as in equation 5.18:

$$\begin{aligned}\bar{\pi}_{R4} &= y\big(\pi_{R4-C}\big) + \big(1-y\big)\big(\pi_{R4-N}\big) \\ &= zs - y\big[z\big(\beta s + I\big) + c_3\big] - \big(1-y\big)xp\end{aligned} \tag{5.42}$$

The expected payoffs of the energy networks from cooperation is the same as in equations 5.7, 5.19 and 5.31:

$$\begin{aligned}\pi_{EN4-C} &= x\big[y\big(\pi_{EN4-1}\big) + \big(1-y\big)\big(\pi_{EN4-3}\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN4-4}\big) + \big(1-y\big)\big(\pi_{EN4-7}\big)\big] \\ &= y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\end{aligned} \tag{5.43}$$

The expected payoffs of the energy networks from non-cooperation is the same as in equations 5.8, 5.20 and 5.32:

$$\begin{aligned}\pi_{EN4-N} &= x\big[y\big(\pi_{EN4-2}\big) + \big(1-y\big)\big(\pi_{EN4-5}\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN4-6}\big) + \big(1-y\big)\big(\pi_{EN4-8}\big)\big] \\ &= 0\end{aligned} \tag{5.44}$$

The average expected payoffs of the energy networks is the same as in equations 5.9, 5.21 and 5.33:

$$
\begin{aligned}
\bar{\pi}_{EN4} &= z\big(\pi_{EN4-C}\big) + \big(1-z\big)\big(\pi_{EN4-N}\big) \\
&= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]
\end{aligned}
\tag{5.45}
$$

Then, the replicator dynamics equations can be set up for case 4. The replicator dynamics equation for the cooperation strategy of the Commission:

$$
\begin{aligned}
F\big(x\big)_4 = \frac{dx}{dt} &= x\big(\pi_{EC4-C} - \bar{\pi}_{EC4}\big) \\
&= x\big[z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 - \big(1-y\big)c_2 \\
&\quad - \big(z\big(E_1 + E_2\big) - E_2 - x\big(c_1 + \big(1-y\big)c_2\big) - \big(1-x\big)q - zF\big(x\alpha_1 + \big(1-x\big)\alpha_2\big)\big)\big] \\
&= x\big(1-x\big)\big[zF\big(\alpha_2 - \alpha_1\big) - c_1 - \big(1-y\big)c_2 + q\big]
\end{aligned}
\tag{5.46}
$$

The replicator dynamics equation for the cooperation strategy of the regulators is the same as in equation 5.23:

$$
\begin{aligned}
F\big(y\big)_4 = \frac{dy}{dt} &= y\big(\pi_{R4-C} - \bar{\pi}_{R4}\big) \\
&= y\big(1-y\big)\big[xp - z\big(\beta s + I\big) - c_3\big]
\end{aligned}
\tag{5.47}
$$

The replicator dynamics equation for the cooperation strategy of the energy networks is the same as in equations 5.12, 5.24 and 5.36:

$$
\begin{aligned}
F\big(z\big)_4 = \frac{dz}{dt} &= z\big(\pi_{EN1-C} - \bar{\pi}_{EN1}\big) \\
&= z\big(1-z\big)\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]
\end{aligned}
\tag{5.48}
$$

5.2 Equilibrium and Stability Analysis

As mentioned in section 4.1, when the replicator dynamics equation reaches a stable state in iteration, the given strategy is an ESS. Hence, in order to derive the possible ESSs of the game, I first solve the following dynamic differential system (Liu et al., 2021):

$$
\begin{cases}
F(x) = 0 \\
F(y) = 0 \\
F(z) = 0
\end{cases}
\tag{5.49}
$$

After deriving the equilibrium points from solving this system of equations, I conduct a stability analysis using the Jacobian matrix as described in section 4.1 in order to establish whether each equilibrium point can be an ESS. Sections 5.2.1, 5.2.2, 5.2.3 and 5.2.4 present the results of the game in each of the four cases.

5.2.1 Case 1

To derive the equilibrium points for the first case of the game, I insert equations 5.10, 5.11 and 5.12 into equation 5.49 and obtain the following system of equations:

$$\begin{cases} F\left(x\right)_1 = x\left(1-x\right)\left[zF\left(\alpha_2-\alpha_1\right)-c_1\right]=0 \\ F\left(y\right)_1 = y\left(1-y\right)\left[-z\left(\beta s+I\right)-c_3\right]=0 \\ F\left(z\right)_1 = z\left(1-z\right)\left[y\left(\beta s+I\right)-I+\left(x\alpha_1+\left(1-x\right)\alpha_2\right)F\right]=0 \end{cases} \tag{5.50}$$

By solving for x, y and z, I arrive at Proposition 1:

Proposition 1 *The dynamic differential system in equation 5.50 has eight equilibrium points, $E(x,y,z)$, in pure strategies: $E_1\left(0,0,0\right)$, $E_2\left(1,0,0\right)$, $E_3\left(0,1,0\right)$, $E_4\left(0,0,1\right)$, $E_5\left(1,1,0\right)$, $E_6\left(1,0,1\right)$, $E_7\left(0,1,1\right)$ and $E_8\left(1,1,1\right)$.*

Proof 1 *When $x=0$ or $x=1$, $y=0$ or $y=1$ and $z=0$ or $z=1$, then $F(x)_1=0$, $F(y)_1=0$ and $F(z)_1=0$. Hence, E_1-E_8 are equilibrium points of the dynamic differential system in equation 5.50. Since the players can play no other pure strategies, these are the only equilibrium points in pure strategies of the dynamic differential system.*

As mentioned in the introduction to this chapter, the stability of all equilibrium points that involve cooperation from the energy networks will be examined. This concerns $E_4\left(0,0,1\right)$, $E_6\left(1,0,1\right)$, $E_7\left(0,1,1\right)$ and $E_8\left(1,1,1\right)$. This is done by setting up the Jacobian matrix as described in section 4.1:

$$J = \begin{bmatrix} \frac{\partial F(x)_1}{\partial x} & \frac{\partial F(x)_1}{\partial y} & \frac{\partial F(x)_1}{\partial z} \\ \frac{\partial F(y)_1}{\partial x} & \frac{\partial F(y)_1}{\partial y} & \frac{\partial F(y)_1}{\partial z} \\ \frac{\partial F(z)_1}{\partial x} & \frac{\partial F(z)_1}{\partial y} & \frac{\partial F(z)_1}{\partial z} \end{bmatrix} \tag{5.51}$$

Then, each of the four equilibrium points of interest is, one at a time, inserted into the matrix in order to determine the stability of each point. See appendix B.1 for all interim calculations.

$\mathbf{E_4(0,0,1)}$

After substituting $E_4(0,0,1)$ into the Jacobian matrix, it reduces to:

$$J = \begin{bmatrix} F\left(\alpha_2-\alpha_1\right)-c_1 & 0 & 0 \\ 0 & -\beta s-I-c_3 & 0 \\ 0 & 0 & I-\alpha_2 F \end{bmatrix} \tag{5.52}$$

Then, following the procedure described in section 4.1 of deriving the eigenvalues of the Jacobian matrix, the following must hold:

$$\begin{cases} F\left(\alpha_2-\alpha_1\right)-c_1<0 \\ -\beta s-I-c_3<0 \\ I-\alpha_2 F<0 \end{cases} \tag{5.53}$$

For the last condition to hold, the expected external funding the energy networks would receive for an investment in innovation if the Commission did not change its legislation should exceed the investment paid by the energy networks. This is not realistic, meaning the equilibrium point is not stable.

$\mathbf{E_6(1,0,1)}$

After substituting $E_6(1,0,1)$ into the Jacobian matrix, it reduces to:

$$J=\begin{bmatrix} -F\left(\alpha_2-\alpha_1\right)+c_1 & 0 & 0 \\ 0 & -\beta s-I-c_3 & 0 \\ 0 & 0 & I-\alpha_1 F \end{bmatrix} \tag{5.54}$$

Then, the following must hold:

$$\begin{cases} -F\left(\alpha_2-\alpha_1\right)+c_1<0 \\ -\beta s-I-c_3<0 \\ I-\alpha_1 F<0 \end{cases} \tag{5.55}$$

Since all parameters are greater than or equal to zero and $\alpha_2<\alpha_1$, cf. table 4.1, the first condition can never hold. Furthermore, even if the Commission does pass its new legislation it does not seem realistic that the expected external funding the energy networks would receive for an investment in innovation should exceed the investment paid by the energy networks which must be the case for the last condition to hold. Thus, this is not a stable equilibrium either.

$\mathbf{E_7(0,1,1)}$

When substituting $E_7(0,1,1)$ into the Jacobian matrix, it reduces to:

$$J=\begin{bmatrix} F\left(\alpha_2-\alpha_1\right)-c_1 & 0 & 0 \\ 0 & \beta s+I+c_3 & 0 \\ 0 & 0 & -\beta s-\alpha_2 F \end{bmatrix} \tag{5.56}$$

Then, the following must hold:

$$\begin{cases} F\left(\alpha_2-\alpha_1\right)-c_1<0 \\ \beta s+I+c_3<0 \\ -\beta s-\alpha_2 F<0 \end{cases} \tag{5.57}$$

Since all parameters are greater than or equal to zero, the middle condition can never hold. Thus, the equilibrium is unstable.

$\mathbf{E_8(1,1,1)}$

When substituting $E_8(1,1,1)$ into the Jacobian matrix, it reduces to:

$$J=\begin{bmatrix} -F\left(\alpha_2-\alpha_1\right)+c_1 & 0 & 0 \\ 0 & \beta s+I+c_3 & 0 \\ 0 & 0 & -\beta s-\alpha_1 F \end{bmatrix} \tag{5.58}$$

Then, the following must hold:

$$\begin{cases} -F\left(\alpha_2-\alpha_1\right)+c_1<0 \\ \beta s+I+c_3<0 \\ -\beta s-\alpha_1 F<0 \end{cases} \tag{5.59}$$

Following the same argumentation as for equations 5.55 and 5.57, respectively, the first and middle conditions cannot hold, meaning the equilibrium point is unstable. Altogether, this implies that none of the equilibrium points that involve cooperation from the energy networks can be stable in case 1.

5.2.2 Case 2: The Commission can penalize the regulators

To derive the equilibrium points for the second case of the game, I insert equations 5.22, 5.23 and 5.24 into equation 5.49 and obtain the following system of equations:

$$\begin{cases} F\big(x\big)_2=x\big(1-x\big)\big[zF\big(\alpha_2-\alpha_1\big)-c_1-\big(1-y\big)c_2\big]=0 \\ F\big(y\big)_2=y\big(1-y\big)\big[xp-z\big(\beta s+I\big)-c_3\big]=0 \\ F\big(z\big)_2=z\big(1-z\big)\big[y\big(\beta s+I\big)-I+\big(x\alpha_1+\big(1-x\big)\alpha_2\big)F\big] \end{cases} \tag{5.60}$$

By solving for x, y and z, I arrive at Proposition 2, which resembles Proposition 1:

Proposition 2 *The dynamic differential system in equation 5.60 has eight equilibrium points, $E(x,y,z)$, in pure strategies: $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$ and $E_8(1,1,1)$.*

Proof 2 *When $x=0$ or $x=1$, $y=0$ or $y=1$ and $z=0$ or $z=1$, then $F(x)_2=0$, $F(y)_2=0$ and $F(z)_2=0$. Hence, E_1-E_8 are equilibrium points of the dynamic differential system in equation*

5.60. Since the players can play no other pure strategies, these are the only equilibrium points in pure strategies of the dynamic differential system.

As in case 1, the stability of equilibrium points $E_4\,(0,0,1)$, $E_6\,(1,0,1)$, $E_7\,(0,1,1)$ and $E_8\,(1,1,1)$ is examined. Again, this is done by setting up the Jacobian matrix:

$$J = \begin{bmatrix} \frac{\partial F(x)_2}{\partial x} & \frac{\partial F(x)_2}{\partial y} & \frac{\partial F(x)_2}{\partial z} \\ \\ \frac{\partial F(y)_2}{\partial x} & \frac{\partial F(y)_2}{\partial y} & \frac{\partial F(y)_2}{\partial z} \\ \\ \frac{\partial F(z)_2}{\partial x} & \frac{\partial F(z)_2}{\partial y} & \frac{\partial F(z)_2}{\partial z} \end{bmatrix} \tag{5.61}$$

Then, each of the equilibrium points, one after another, can be substituted into the matrix in order to determine whether the points are stable. See appendix B.2 for all interim calculations.

$\mathbf{E_4(0,0,1)}$

When substituting $E_4(0,0,1)$ into the Jacobian matrix, it reduces to:

$$J = \begin{bmatrix} F\left(\alpha_2-\alpha_1\right)-c_1-c_2 & 0 & 0 \\ \\ 0 & -\beta s - I - c_3 & 0 \\ \\ 0 & 0 & I-\alpha_2 F \end{bmatrix} \tag{5.62}$$

Then, the following must hold:

$$\begin{cases} F\left(\alpha_2-\alpha_1\right)-c_1-c_2 < 0 \\ -\beta s - I - c_3 < 0 \\ I-\alpha_2 F < 0 \end{cases} \tag{5.63}$$

Following the same argumentation as for equation 5.53, the last condition cannot realistically hold. Thus, the equilibrium point is not stable.

$\mathbf{E_6(1,0,1)}$

When substituting $E_6(1,0,1)$ into the Jacobian matrix, it reduces to:

$$J = \begin{bmatrix} -F\left(\alpha_2-\alpha_1\right)+c_1+c_2 & 0 & 0 \\ \\ 0 & p-\beta s - I - c_3 & 0 \\ \\ 0 & 0 & I-\alpha_1 F \end{bmatrix} \tag{5.64}$$

Then, the following must hold:

$$\begin{cases} -F\left(\alpha_2-\alpha_1\right)+c_1+c_2<0 \\ p-\beta s-I-c_3<0 \\ I-\alpha_1 F<0 \end{cases} \tag{5.65}$$

Following the same argumentation as for equation 5.55, the first condition can never hold, while the last condition cannot realistically hold, meaning the equilibrium point is unstable.

$\mathbf{E_7(0,1,1)}$

By substituting $E_7(0,1,1)$ into the Jacobian matrix, it reduces to:

$$J=\begin{bmatrix} F\left(\alpha_2-\alpha_1\right)-c_1 & 0 & 0 \\ 0 & \beta s+I+c_3 & 0 \\ 0 & 0 & -\beta s-\alpha_2 F \end{bmatrix} \tag{5.66}$$

Then, the following must hold:

$$\begin{cases} F\left(\alpha_2-\alpha_1\right)-c_1<0 \\ \beta s+I+c_3<0 \\ -\beta s-\alpha_2 F<0 \end{cases} \tag{5.67}$$

Following the same argumentation as for equation 5.57, the middle condition can never hold. Hence, the equilibrium point is unstable.

$\mathbf{E_8(1,1,1)}$

By substituting $E_8(1,1,1)$ into the Jacobian matrix, it reduces to:

$$J=\begin{bmatrix} -F\left(\alpha_2-\alpha_1\right)+c_1 & 0 & 0 \\ 0 & -p+\beta s+I+c_3 & 0 \\ 0 & 0 & -\beta s-\alpha_1 F \end{bmatrix} \tag{5.68}$$

Then, the following must hold:

$$\begin{cases} -F\left(\alpha_2-\alpha_1\right)+c_1<0 \\ -p+\beta s+I+c_3<0 \\ -\beta s-\alpha_1 F<0 \end{cases} \tag{5.69}$$

Following the same argumentation as for equation 5.55, the first condition can never hold, meaning the equilibrium point is unstable. To sum up, this means that none of the equilibrium points involving cooperation from the energy networks can be stable in case 2 either.

5.2.3 Case 3: Penalty on the Commission for not cooperating

To derive the equilibrium points for the third case of the game, I insert equations 5.34, 5.35 and 5.36 into equation 5.49 and obtain the following system of equations:

$$\begin{cases} F(x)_3 = x(1-x)\left[zF(\alpha_2-\alpha_1)-c_1+q\right]=0 \\ F(y)_3 = y(1-y)\left[-z(\beta s+I)-c_3\right]=0 \\ F(z)_3 = z(1-z)\left[y(\beta s+I)-I+(x\alpha_1+(1-x)\alpha_2)F\right] \end{cases} \tag{5.70}$$

By solving for x, y and z, I arrive at Proposition 3, which corresponds to Propositions 1 and 2:

Proposition 3 *The dynamic differential system in equation 5.70 has eight equilibrium points, $E(x,y,z)$, in pure strategies: $E_1\,(0,0,0)$, $E_2\,(1,0,0)$, $E_3\,(0,1,0)$, $E_4\,(0,0,1)$, $E_5\,(1,1,0)$, $E_6\,(1,0,1)$, $E_7\,(0,1,1)$ and $E_8\,(1,1,1)$.*

Proof 3 *When $x=0$ or $x=1$, $y=0$ or $y=1$ and $z=0$ or $z=1$, then $F(x)_3=0$, $F(y)_3=0$ and $F(z)_3=0$. Hence, E_1-E_8 are equilibrium points of the dynamic differential system in equation 5.70. Since the players can play no other pure strategies, these are the only equilibrium points in pure strategies of the dynamic differential system.*

As in case 1 and case 2, the stability of equilibrium points $E_4\,(0,0,1)$, $E_6\,(1,0,1)$, $E_7\,(0,1,1)$ and $E_8\,(1,1,1)$ is examined by means of the Jacobian matrix:

$$J=\begin{bmatrix} \frac{\partial F(x)_3}{\partial x} & \frac{\partial F(x)_3}{\partial y} & \frac{\partial F(x)_3}{\partial z} \\ \frac{\partial F(y)_3}{\partial x} & \frac{\partial F(y)_3}{\partial y} & \frac{\partial F(y)_3}{\partial z} \\ \frac{\partial F(z)_3}{\partial x} & \frac{\partial F(z)_3}{\partial y} & \frac{\partial F(z)_3}{\partial z} \end{bmatrix} \tag{5.71}$$

Then, the four equilibrium points can be substituted into the matrix in order to determine whether they are stable. See appendix B.3 for all interim calculations.

$\mathbf{E_4(0,0,1)}$

By substituting $E_4(0,0,1)$ into the Jacobian matrix, it reduces to:

$$J=\begin{bmatrix} F(\alpha_2-\alpha_1)-c_1+q & 0 & 0 \\ 0 & -\beta s-I-c_3 & 0 \\ 0 & 0 & I-\alpha_2 F \end{bmatrix} \tag{5.72}$$

Then, the following must hold:

$$\begin{cases} F\left(\alpha_2-\alpha_1\right)-c_1+q<0 \\ -\beta s-I-c_3<0 \\ I-\alpha_2 F<0 \end{cases} \tag{5.73}$$

Following the argumentation for equation 5.53, the last condition cannot realistically hold. For this reason, the point is unstable.

$\mathbf{E_6(1,0,1)}$

By substituting $E_6(1,0,1)$ into the Jacobian matrix, it reduces to:

$$J=\begin{bmatrix} -F\left(\alpha_2-\alpha_1\right)+c_1-q & 0 & 0 \\ 0 & -\beta s-I-c_3 & 0 \\ 0 & 0 & I-\alpha_1 F \end{bmatrix} \tag{5.74}$$

Then, the following must hold:

$$\begin{cases} -F\left(\alpha_2-\alpha_1\right)+c_1-q<0 \\ -\beta s-I-c_3<0 \\ I-\alpha_1 F<0 \end{cases} \tag{5.75}$$

Following the same argumentation as for equation 5.55, the first condition can never hold while the last condition cannot realistically hold. Thus, the point is unstable.

$\mathbf{E_7(0,1,1)}$

When substituting $E_7(0,1,1)$ into the Jacobian matrix, it reduces to:

$$J=\begin{bmatrix} F\left(\alpha_2-\alpha_1\right)-c_1+q & 0 & 0 \\ 0 & \beta s+I+c_3 & 0 \\ 0 & 0 & -\beta s-\alpha_2 F \end{bmatrix} \tag{5.76}$$

Then, the following must hold:

$$\begin{cases} F\left(\alpha_2-\alpha_1\right)-c_1+q<0 \\ \beta s+I+c_3<0 \\ -\beta s-\alpha_2 F<0 \end{cases} \tag{5.77}$$

As argued for equation 5.57, the middle condition can never hold, meaning the equilibrium point is not stable.

$\mathbf{E_8(1,1,1)}$

When substituting $E_8(1,1,1)$ into the Jacobian matrix, it reduces to:

$$J = \begin{bmatrix} -F(\alpha_2 - \alpha_1) + c_1 - q & 0 & 0 \\ \\ 0 & \beta s + I + c_3 & 0 \\ \\ 0 & 0 & -\beta s - \alpha_1 F \end{bmatrix} \tag{5.78}$$

Then, the following must hold:

$$\begin{cases} -F(\alpha_2 - \alpha_1) + c_1 - q + q < 0 \\ \beta s + I + c_3 < 0 \\ -\beta s - \alpha_1 F < 0 \end{cases} \tag{5.79}$$

Following the argumentation for equation 5.57, the middle condition can never hold, meaning the equilibrium point is not stable.

5.2.4 Case 4: The Commission can penalize the regulators and will be penalized for not cooperating

To derive the equilibrium points for the fourth and last case of the game, I insert equations 5.46, 5.47 and 5.48 into equation 5.49 and obtain the following system of equations:

$$\begin{cases} F(x)_4 = x(1-x)\big[zF(\alpha_2 - \alpha_1) - c_1 - (1-y)c_2 + q\big] = 0 \\ F(y)_4 = y(1-y)\big[xp - z(\beta s + I) - c_3\big] = 0 \\ F(z)_4 = z(1-z)\big[y(\beta s + I) - I + (x\alpha_1 + (1-x)\alpha_2)F\big] = 0 \end{cases} \tag{5.80}$$

By solving for x, y and z, I arrive at Proposition 4, which corresponds to Propositions 1, 2 and 3:

Proposition 4 *The dynamic differential system in equation 5.80 has eight equilibrium points, $E(x, y, z)$, in pure strategies: $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$ and $E_8(1,1,1)$.*

Proof 4 *When $x = 0$ or $x = 1$, $y = 0$ or $y = 1$ and $z = 0$ or $z = 1$, then $F(x)_4 = 0$, $F(y)_4 = 0$ and $F(z)_4 = 0$. Hence, $E_1 - E_8$ are equilibrium points of the dynamic differential system in equation 5.80. Since the players can play no other pure strategies, these are the only equilibrium points in pure strategies of the dynamic differential system.*

As in the three previous cases, the stability of equilibrium points $E_4(0,0,1)$, $E_6(1,0,1)$, $E_7(0,1,1)$

and $E_8\,(1,1,1)$ is examined by means of the Jacobian matrix:

$$J = \begin{bmatrix} \frac{\partial F(x)_4}{\partial x} & \frac{\partial F(x)_4}{\partial y} & \frac{\partial F(x)_4}{\partial z} \\ \\ \frac{\partial F(y)_4}{\partial x} & \frac{\partial F(y)_4}{\partial y} & \frac{\partial F(y)_4}{\partial z} \\ \\ \frac{\partial F(z)_4}{\partial x} & \frac{\partial F(z)_4}{\partial y} & \frac{\partial F(z)_4}{\partial z} \end{bmatrix} \tag{5.81}$$

Then, the four equilibrium points can be substituted into the matrix in order to determine whether they are stable. See appendix B.4 for all interim calculations.

$\mathbf{E_4(0,0,1)}$

By substituting $E_4(0,0,1)$ into the Jacobian matrix, it reduces to:

$$J = \begin{bmatrix} F\,(\alpha_2-\alpha_1)-c_1-c_2+q & 0 & 0 \\ \\ 0 & -\beta s - I - c_3 & 0 \\ \\ 0 & 0 & I-\alpha_2 F \end{bmatrix} \tag{5.82}$$

Then, the following must hold:

$$\begin{cases} F\,(\alpha_2-\alpha_1)-c_1-c_2+q < 0 \\ -\beta s - I - c_3 < 0 \\ I-\alpha_2 F < 0 \end{cases} \tag{5.83}$$

Following the argumentation for equation 5.53, the last condition cannot realistically hold. This means the equilibrium point is not stable.

$\mathbf{E_6(1,0,1)}$

By substituting $E_6(1,0,1)$ into the Jacobian matrix, it reduces to:

$$J = \begin{bmatrix} -F\,(\alpha_2-\alpha_1)+c_1+c_2-q & 0 & 0 \\ \\ 0 & p-\beta s - I - c_3 & 0 \\ \\ 0 & 0 & I-\alpha_1 F \end{bmatrix} \tag{5.84}$$

Then, the following must hold:

$$\begin{cases} -F\left(\alpha_2 - \alpha_1\right) + c_1 + c_2 - q < 0 \\ p - \beta s - I - c_3 < 0 \\ I - \alpha_1 F < 0 \end{cases} \tag{5.85}$$

Following the argumentation for equation 5.55, the first condition can never hold, while the last condition cannot realistically hold. Thus, the point is unstable.

$\mathbf{E_7(0,1,1)}$

By substituting $E_7(0,1,1)$ into the Jacobian matrix, it reduces to:

$$J = \begin{bmatrix} F\left(\alpha_2 - \alpha_1\right) - c_1 + q & 0 & 0 \\ 0 & \beta s + I + c_3 & 0 \\ 0 & 0 & -\beta s - \alpha_2 F \end{bmatrix} \tag{5.86}$$

Then, the following must hold:

$$\begin{cases} F\left(\alpha_2 - \alpha_1\right) - c_1 + q < 0 \\ \beta s + I + c_3 < 0 \\ -\beta s - \alpha_2 F < 0 \end{cases} \tag{5.87}$$

Following the argumentation for equation 5.57, the middle condition can never hold, meaning the point is unstable.

$\mathbf{E_8(1,1,1)}$

By substituting $E_8(1,1,1)$ into the Jacobian matrix, it reduces to:

$$J = \begin{bmatrix} -F\left(\alpha_2 - \alpha_1\right) + c_1 - q & 0 & 0 \\ 0 & -p + \beta s + I + c_3 & 0 \\ 0 & 0 & -\beta s - \alpha_2 F \end{bmatrix} \tag{5.88}$$

Then, the following must hold:

$$\begin{cases} -F\left(\alpha_2 - \alpha_1\right) + c_1 - q < 0 \\ -p + \beta s + I + c_3 < 0 \\ -\beta s - \alpha_1 F < 0 \end{cases} \tag{5.89}$$

Since all parameters are greater than or equal to zero, cf. table 4.1, the last condition always holds. Then, it can be inferred from equation 5.89 that equilibrium point $E_8(1,1,1)$ is stable if the following two conditions are met:

$$\begin{cases} F\left(\alpha_1 - \alpha_2\right) + c_1 < q \\ \beta s + I + c_3 < p \end{cases} \tag{5.90}$$

The first condition implies that the penalty imposed on the Commission in case it does not choose its cooperation strategy must be greater than the expected additional financing it will pay to the energy networks if they choose to invest and the Commission chooses to change its legislation plus the cost associated with changing regulations. The second condition means that the sum of the penalty imposed on regulators if they choose their non-cooperative strategy while the Commission chooses cooperation must exceed the fraction of the cost reduction given to energy networks and the investment costs which are passed to the consumers, represented by the regulators, in case the energy networks choose to invest in innovation and the regulators change their regulatory practice to one that induces innovation plus the cost of changing the regulatory practice. If this is true, then the equilibrium point is stable. Thus, a number of numerical simulations will be conducted in section 5.3 in order to investigate the effect of the four chosen parameters on the convergence to this equilibrium as described in section 4.3.

5.3 Numerical Simulations

5.3.1 Parameter Assignment

As described in section 4.3, numerical simulations on the ESS $E_8(1,1,1)$ in case 4 will be conducted for four different scenarios. It is assumed that the parameters E_1, E_2, F, α_2, c_1, c_2, c_3, s and I are given and that α_1, β, p and q are adjustable, since these are the results of potential policies set by the Commission and the regulators. Thus, they will be referred to as policy parameters from now on. All parameters are chosen so that the conditions derived in equation 5.90 are met. This is evident from figure 5.1 which shows the evolutionary process of the three groups of players towards the ESS. From this figure, it can be seen that the players converge to the stable equilibrium point $E_8(1,1,1)$ in all four scenarios.

From looking at the replicator dynamics equations 5.46, 5.47 and 5.48, it is evident that the environmental benefits, E_1, and environmental costs, E_2, which the Commission will get in case the energy networks do or do not, respectively, invest in innovation with decarbonization goals do not affect the convergence towards the ESS. For this reason, these parameters will not be given a value. The values in each of the four scenarios of the seven remaining parameters that are taken as given can be seen from table 5.1. The four policy parameters have been given the same value in all four scenarios, namely $\alpha_1 = 0.8$, $\beta = 0.5$, $p = 4$ and $q = 4$. Then, sensitivity analyses are conducted using MATLAB for the four parameters in all four scenarios by decreasing and increasing, respectively, these values by 25%. Furthermore, each of these sensitivity analyses are conducted for initial probabilities $x_0 = y_0 = z_0 = 0.2$ and $x_0 = y_0 = z_0 = 0.8$. This is done in section 5.3.2.1. In addition to this, sensitivity analyses are conducted for the initial probabilities x, y and z in order to investigate the impact of relatively low and relatively high, respectively, initial probabilities on the convergence towards the stable state. This is done in section 5.3.2.2. All code can be found in appendix C.

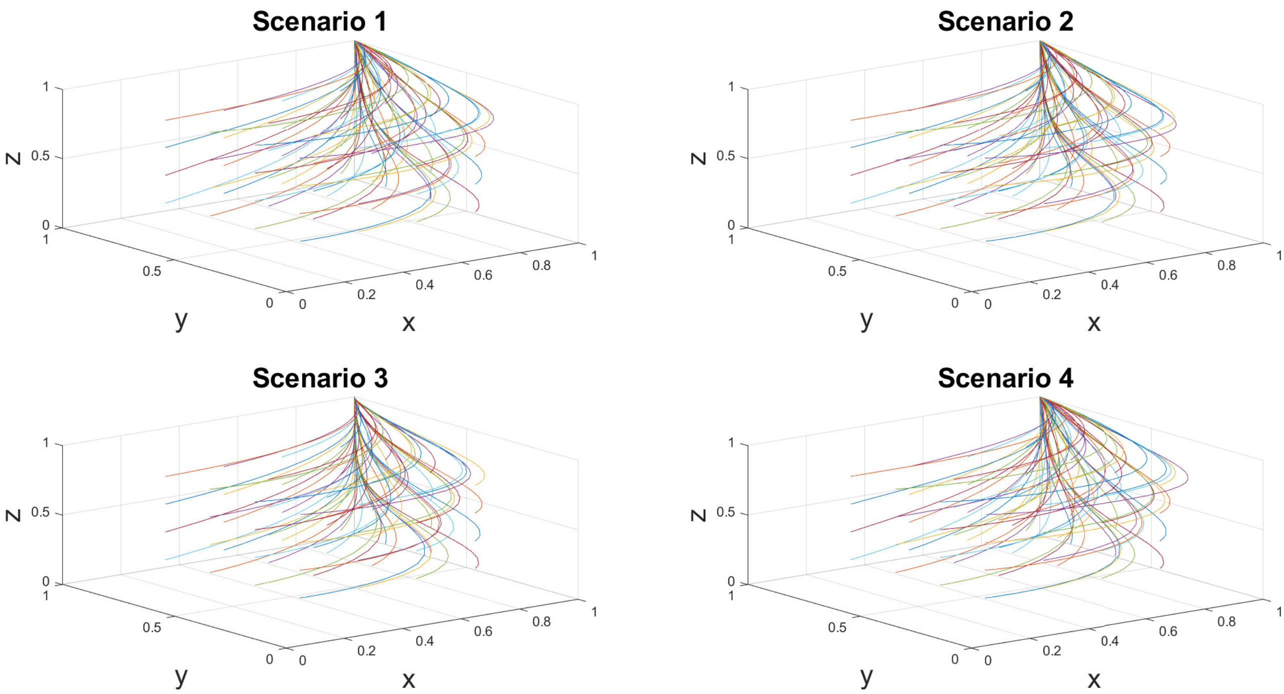

Figure 5.1: Evolutionary process of the three groups of players towards the ESS $E_8(1, 1, 1)$ in each of the four scenarios.

Parameter	Scenario 1 value	Scenario 2 value	Scenario 3 value	Scenario 4 value
F	1	0.75	1	1
α_2	0.5	0.4	0.5	0.5
c_1	0.5	0.5	0.5	0.7
c_2	0.5	0.5	0.5	0.7
c_3	0.5	0.5	0.5	0.7
I	1	1	1	1
s	2	2	1	2

Table 5.1: Parameter values in the four different scenarios.

5.3.2 Sensitivity Analyses

5.3.2.1 Sensitivity Analyses of Policy Parameters

Figure 5.2 shows the impact of a change in α_1 on the convergence rate of x, y and z to the equilibrium in the four different scenarios. From looking at the figure, it is clear that the value of α_1 only has little to no impact on the convergence of x and y to the ESS. On the other hand, α_1 does seem to have an impact on the convergence of z to the ESS for a low initial probability z_0. Then, a higher value of α_1 seems to result in a quicker convergence towards the stable state. For a higher initial value z_0, it seems there is still some positive effect on the convergence rate of a higher value of α_1, but this effect seems to be more or less insignificant. From looking at figure 5.3, it seems that the effect of a value change in α_1 and β has almost the same effect on the convergence towards the stable state, qualitatively speaking. Again, for a low initial probability z_0, a higher value of β seems to result in a quicker convergence towards the ESS while changing β seems to have little to no effect on the convergence rate of x. However, one distinction is that a higher β value seems to result in a slightly slower convergence rate for y in all scenarios except scenario 3. As for the case of α_1, there also seems to be a small, but more or less insignificant, positive effect of β on the convergence rate of z for high initial probabilities z_0.

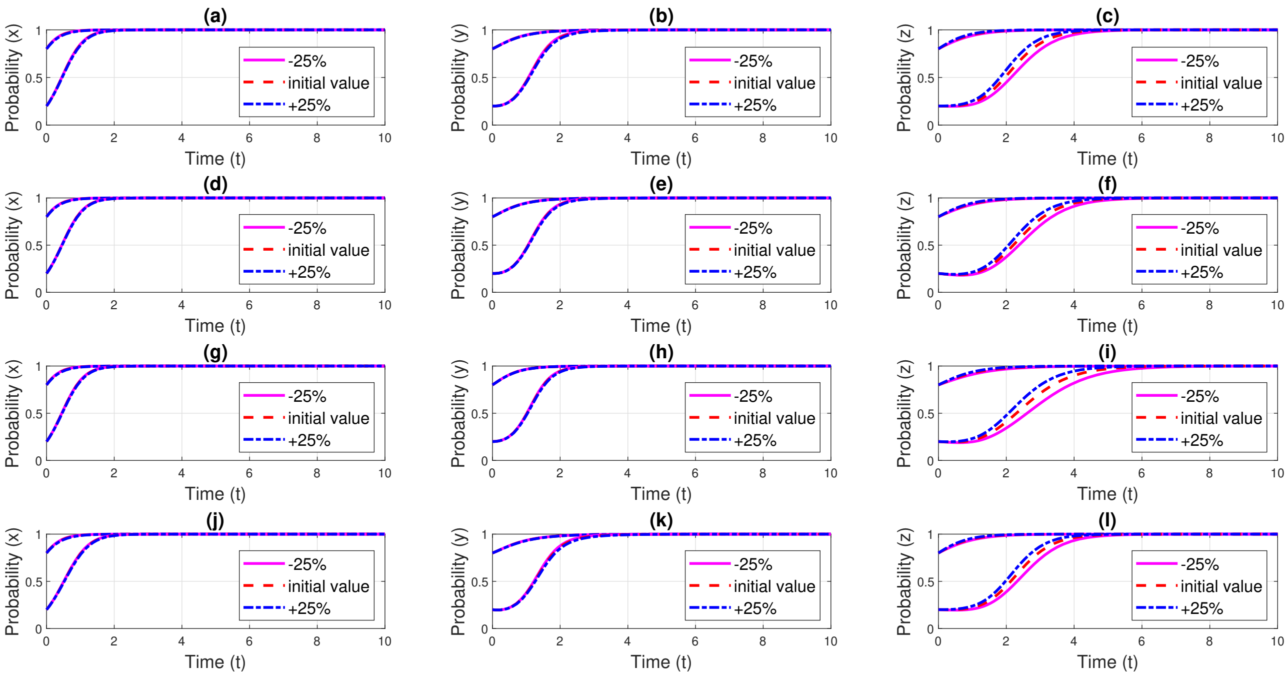

Figure 5.2: Sensitivity analysis of α_1. (a), (b) and (c) show the sensitivity analyses in scenario 1, (d), (e) and (f) show the sensitivity analyses in scenario 2, (g), (h) and (i) show the sensitivity analyses in scenario 3, and (j), (k) and (l) show the sensitivity analyses in scenario 4.

The picture is somewhat different in figure 5.4 which shows the impact of a change in p on the convergence rate of x, y and z to the ESS. Here, it can be seen that a lower p value leads to a much slower convergence of y to the stable state compared to higher values of p, both for high and low initial probabilities y_0. For low initial probabilities z_0, a lower p value also seems to lead to a slower convergence rate. However, also for this policy parameter, the impact on the convergence rate of x for both high and low initial probabilities x_0 plus on the convergence rate of z for high initial probabilities z_0 seems to be small to non-existent. The last policy parameter, q, is interesting in the sense that it seems to be the only one of the four variables that affect the convergence rate of both x, y and z, even in the same direction. As can be seen from figure 5.5, a higher value of q seems to imply a

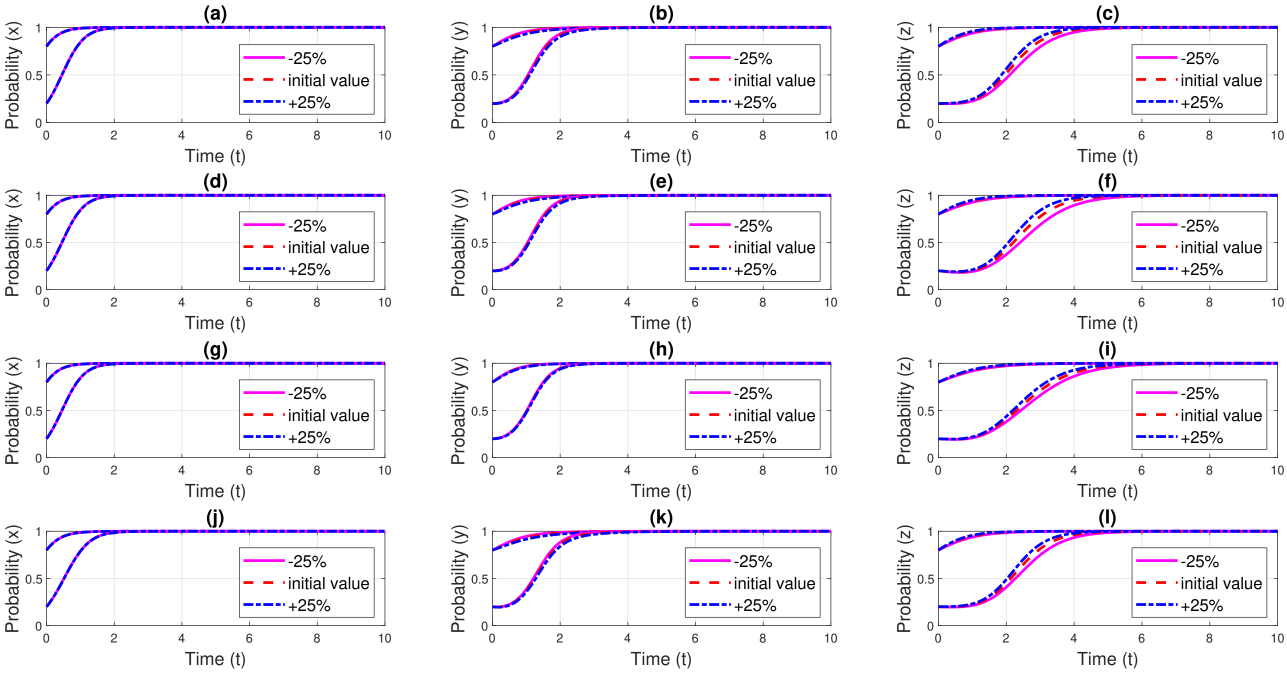

Figure 5.3: Sensitivity analysis of β. (a), (b) and (c) show the sensitivity analyses in scenario 1, (d), (e) and (f) show the sensitivity analyses in scenario 2, (g), (h) and (i) show the sensitivity analyses in scenario 3, and (j), (k) and (l) show the sensitivity analyses in scenario 4.

quicker convergence towards the ESS, particularly for x, but also for low initial probabilities y_0 and z_0. However, for high initial probabilities, the effect on the convergence rate of x from a change in q seems to be somewhat smaller while the effect on the convergence rate of y and z seems to be insignificant.

5.3.2.2 Sensitivity Analyses of Initial Probabilities

After analysing the effect of changing the policy parameters on the convergence rates of x, y and z in section 5.3.2.1, I turn to the sensitivity analyses of the impact of a change in the initial parameters x_0, y_0 and z_0 on the convergence to the equilibrium $E_8(1, 1, 1)$. The point of doing this is to be able to deduce if it makes more sense to initially focus on some of the three groups' convergence to the ESS rather than the others' (Liu et al., 2021). Figure 5.6 shows the impact of a change in the initial probability x_0 on the convergence rate of y and z to the equilibrium in the four different scenarios. The impact does not seem to be immense, but a higher initial probability x_0 does seem to result in a quicker convergence rate for y and z. Especially in scenario 4, this seems to be the case while there seems to be little to no impact in scenario 3. The impact of a change in the initial probability y_0, which can be seen from figure 5.7, seems to be small to non-existent for the convergence rate of x to the ESS. On the other hand, it is clear from looking at figure 5.7 that a higher initial probability y_0 results in a quicker convergence of z to the stable state. The convergence rate of x does not seem to be affected by the initial probability of z either, which can be seen from figure 5.8, but there appears to be a negative effect on the convergence rate of y of a higher initial probability z_0. However, the negative effect does not seem to be distinct.

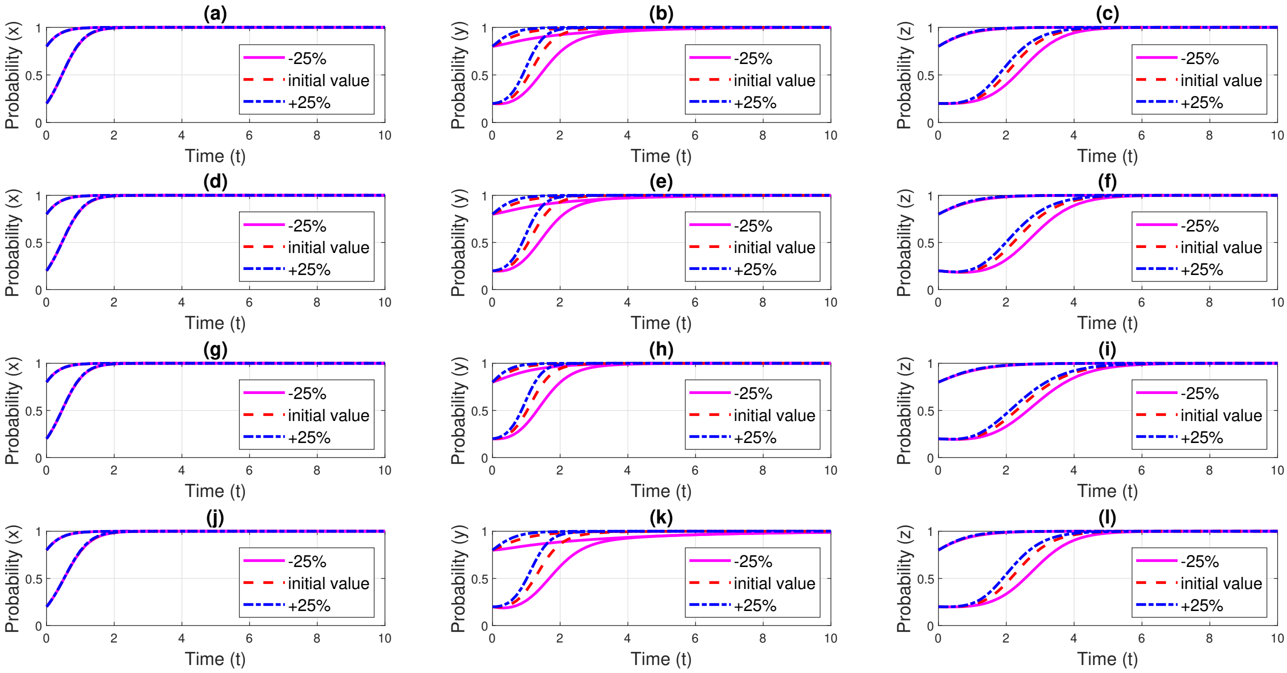

Figure 5.4: Sensitivity analysis of p. (a), (b) and (c) show the sensitivity analyses in scenario 1, (d), (e) and (f) show the sensitivity analyses in scenario 2, (g), (h) and (i) show the sensitivity analyses in scenario 3, and (j), (k) and (l) show the sensitivity analyses in scenario 4.

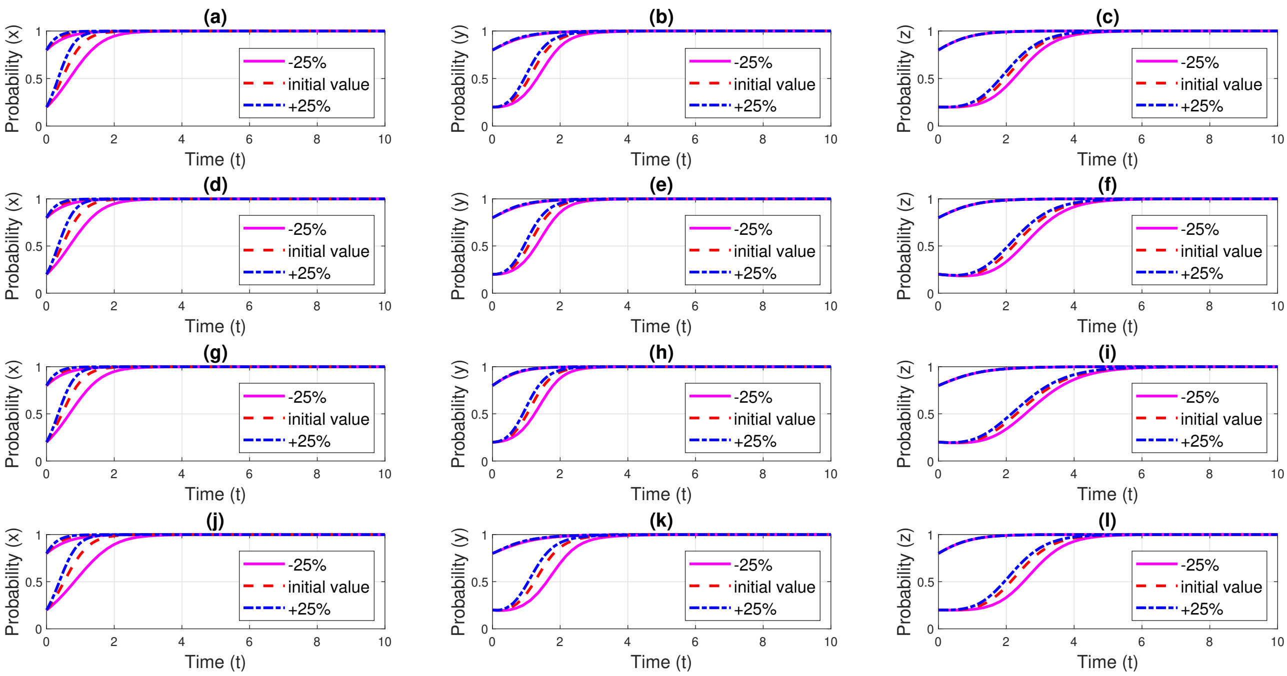

Figure 5.5: Sensitivity analysis of q. (a), (b) and (c) show the sensitivity analyses in scenario 1, (d), (e) and (f) show the sensitivity analyses in scenario 2, (g), (h) and (i) show the sensitivity analyses in scenario 3, and (j), (k) and (l) show the sensitivity analyses in scenario 4.

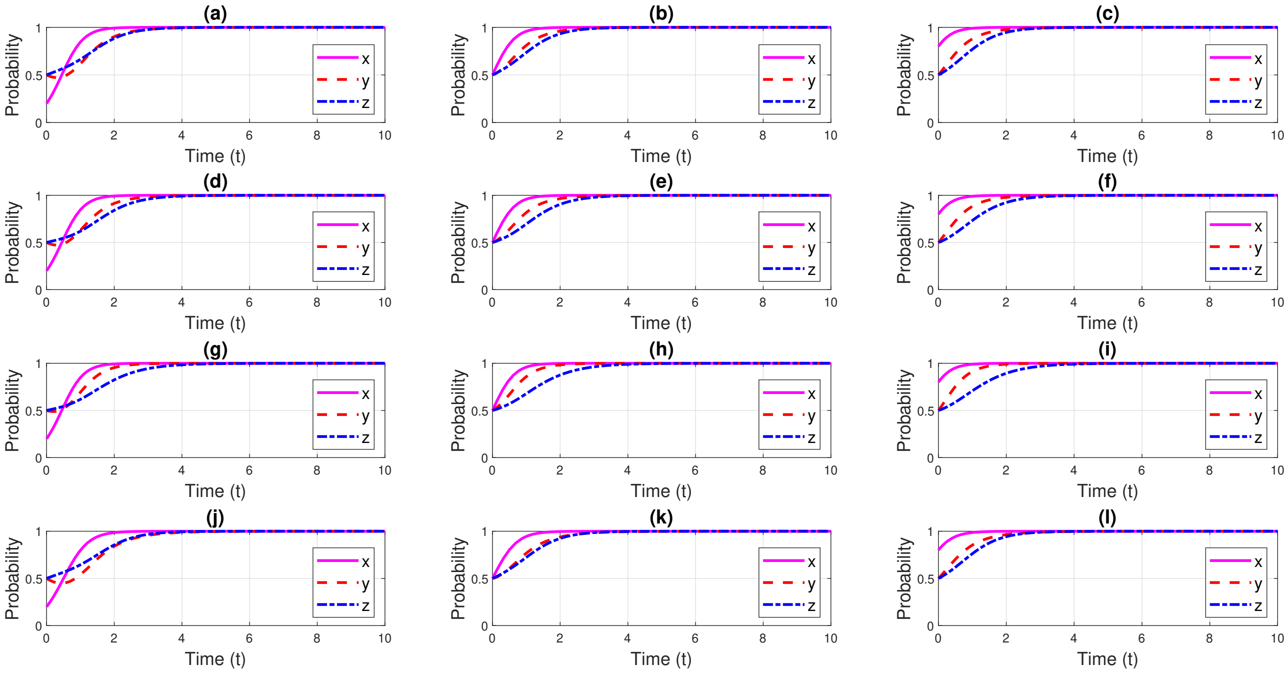

Figure 5.6: Sensitivity analysis of x. (a), (b) and (c) show the sensitivity analyses in scenario 1, (d), (e) and (f) show the sensitivity analyses in scenario 2, (g), (h) and (i) show the sensitivity analyses in scenario 3, and (j), (k) and (l) show the sensitivity analyses in scenario 4.

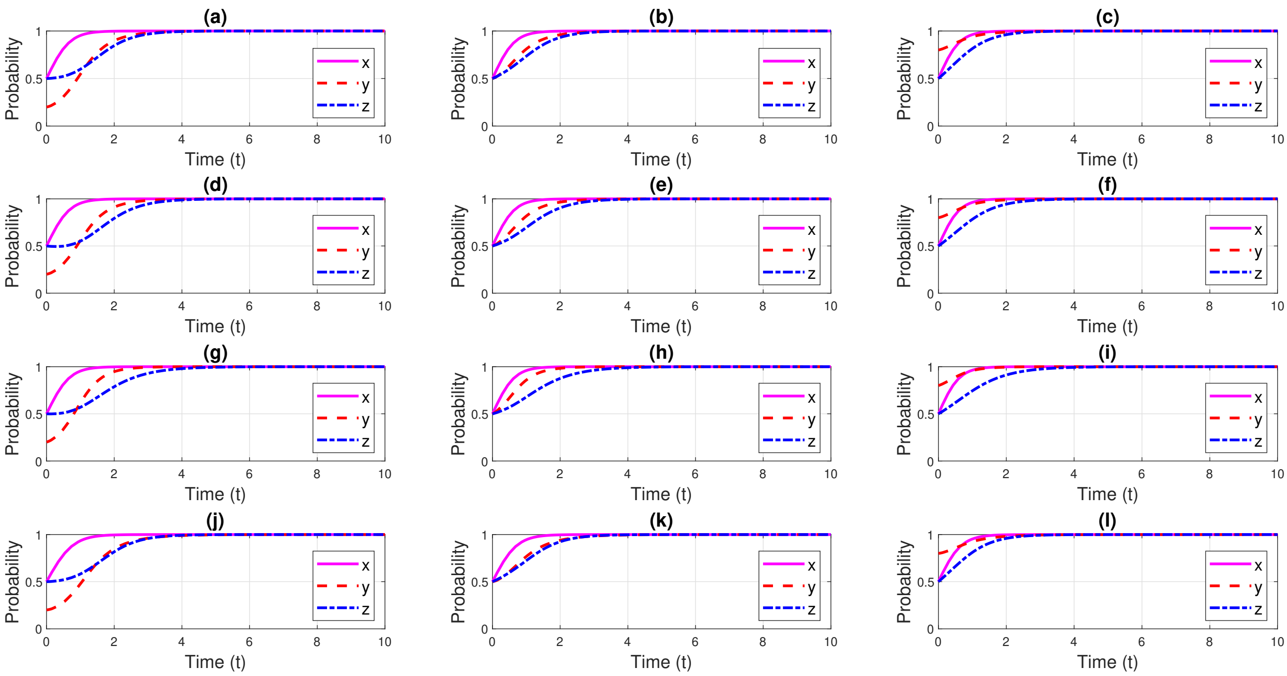

Figure 5.7: Sensitivity analysis of y. (a), (b) and (c) show the sensitivity analyses in scenario 1, (d), (e) and (f) show the sensitivity analyses in scenario 2, (g), (h) and (i) show the sensitivity analyses in scenario 3, and (j), (k) and (l) show the sensitivity analyses in scenario 4.

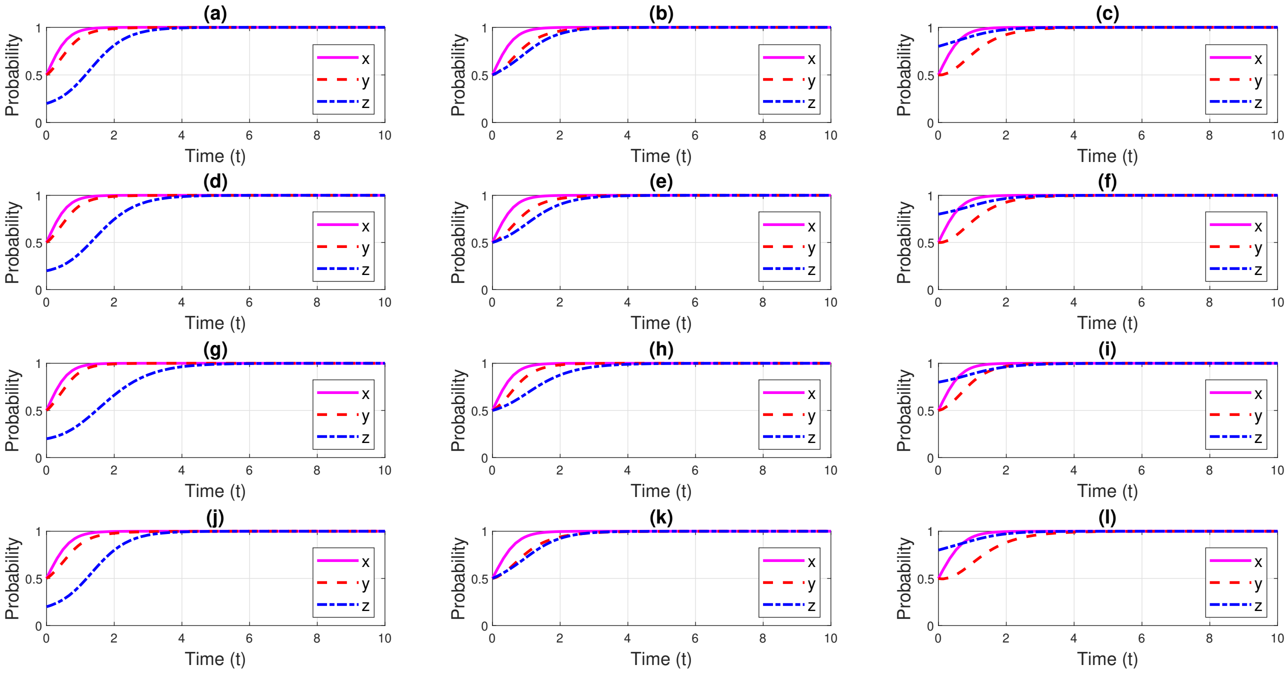

Figure 5.8: Sensitivity analysis of z. (a), (b) and (c) show the sensitivity analyses in scenario 1, (d), (e) and (f) show the sensitivity analyses in scenario 2, (g), (h) and (i) show the sensitivity analyses in scenario 3, and (j), (k) and (l) show the sensitivity analyses in scenario 4.

Chapter 6

Discussion and Policy Implications

On the background of the results of the numerical simulations presented in section 5.3, policy implications of the game are discussed in section 6.1. After this, limitations of the methodology and the game are discussed in section 6.2 where suggestions for extending the research are also presented.

6.1 Policy Implications

As is evident from the research question posed in chapter 1, the main goal of this thesis is to investigate how to encourage energy networks to invest in innovation. From section 5.2, I know that the only potentially stable equilibrium which involves that energy networks invest in innovation is equilibrium $E_8(1, 1, 1)$ in case 4. This equilibrium point involves that the Commission changes its legislation in order to induce innovation in energy networks and that this change in legislation dictates that the regulators change their regulatory mechanism to one that induces innovation. Otherwise, the regulators will be penalized, just as the Commission will be penalized for not changing regulations. Furthermore, the ESS involves that the regulators change their regulatory practice to a combination of an input-based and output-based mechanism with the aim of incentivizing innovation. Lastly, this equilibrium involves that energy networks invest in innovation with decarbonization goals. In order for this equilibrium to be stable, two conditions must be met, as mentioned in section 5.2.4. These conditions essentially imply that the penalties imposed on the Commission and the regulators for not cooperating must exceed their additional expenses of cooperating compared to choosing their non-cooperative strategy, given that the other two groups of players cooperate.

From sections 3.2 and 4.2.1.1, I know that the Commission has already started revising the TEN-E Regulation in order to make it more compatible with reaching the goals of the European Green Deal. Based on this, it seems reasonable to assume that the initial probability x_0 lies at the high end. At the same time, considering the lack of innovation in the energy sector, it seems reasonable to assume that the initial proportion of energy networks investing in innovation with decarbonization goals is on the low end, corresponding to a low initial probability z_0. Likewise, since the majority of regulators today use cost-based regulatory mechanisms or incentive-based mechanisms for incentivizing cost-efficiency as mentioned in section 4.2.1.2, it seems reasonable to assume that the initial probability y_0 is low.

Since the initial probabilities both matter for the convergence rate to the ESS for the other populations and for the impact of changes in the policy variables on the convergence rate to the ESS as can be seen from section 5.3, this is relevant to consider. The assumed high initial probability x_0 alone is presumed to increase the convergence rates of the energy networks and regulators to the stable state $E_8(1,1,1)$ as mentioned in section 5.3.2.2, compared to if x_0 had been lower. However, since it seems to be a smaller effect, it is relevant to consider which policy parameters it might be sound to adjust in order to increase the convergence to the stable state.

As mentioned in section 5.3.2.1, the only one of the so-called policy parameters where a higher value is equivalent to an increase in the convergence rate towards the ESS for all three populations is q, i.e. the penalty imposed on the Commission in case it does not change its legislation. However, the question as to who is responsible for adjusting this parameter is yet to be answered, as mentioned in sections 4.2.2 and 4.3. As stated in section 4.2.2, the assumption that the Commission will receive a penalty if it does not choose its cooperation strategy is argued to hold based on the European Climate Law saying that the Commission is bound to take necessary measures of meeting the legally binding target of net zero greenhouse gas emissions by 2050. It might not be reasonable to believe that the EU will increase a penalty imposed on one of its own institutions. Besides, the power to adjust the parameter q must be assumed to lie beyond the scope of the game presented in this thesis.

Moreover, if I hold on to the assumption that the initial probability of the Commission is high, it might not be of much importance to adjust a parameter that also increases convergence towards the equilibrium point for the Commission. Instead, it could be relevant to look at the parameters which the Commission is responsible for choosing. As mentioned in section 5.3.2.1, for low initial probabilities y_0 and z_0, a higher p increases the convergence rate of both y and z to a high degree compared to the other policy values. Furthermore, as also seen from section 5.3.2.1, an increase in α_1 increases convergence for the energy networks towards the ESS when it is assumed that the initial probability z_0 is low. Since a change in both of these parameters appears to have no impact on the convergence rate of the Commission, it seems like a reasonable way of increasing convergence to the ESS. It appears that the cooperation of the Commission is of great importance when it comes to reaching the stable equilibrium. This is in correspondence with the findings by Yang et al. (2021) and Guo et al. (2021) amongst others who both find that the greater the subsidies and penalties from the government are, the more likely collaboration is, as mentioned in section 2. Furthermore, it supports the findings by Encarnação et al. (2018) who find that if at first the cooperation of the public sector, in this game corresponding to the Commission, is ensured, then incentive mechanisms can be implemented for assuring the cooperation of the remaining groups of players.

6.2 Limitations and Future Research

Both from reviewing comparable studies using evolutionary game theory for moving towards the green transition, as summarized in section 2.3, and from the results derived in chapter 5, as discussed in section 6.1, it becomes clear that the Commission's role in reaching a stable state where energy networks invest in innovation with the aim of decarbonizing the energy section is indispensable. Since the Commission pushes the European Green Deal and is bound to take the necessary measures for reaching the decarbonization goals of this as required by the European Climate Law a different approach to examining the issue of getting energy networks in the EU to increase investment in innovation could be to model the game with the Commission as the social planner who wishes to maximize social welfare, also taking environmental benefits into account. This resembles the approach taken by Cantner and Kuhn (1999) and Rong et al. (2022), as described in section 2.2. However, they model a regulator, not a government authority or equivalent, as the social welfare-minded policy designer. If the game is modelled from this angle, the question of how the penalty on the Commission for not cooperating is determined becomes irrelevant.

However, the issue of the size of q both being highly important for the stability of the equilibrium point, as seen from section 5.2.4, and presumably being determined exogenously in the model set up in section 4.2 is not the only limitation of the research conducted throughout this thesis. The regulatory practices for regulating energy networks differ from Member State to Member State, just as it differs if there are one or more energy networks for electricity and gas, respectively, in each Member State. Hence, how the payoffs of regulators and energy networks are determined from state to state will differ in practice. Furthermore, a lot of the suggestions in the academic literature for especially which initiatives the Commission can start in order to increase innovation in energy networks are difficult to translate into payoffs, as seen, for example, in section 4.2.1.1, for which reason it is difficult to examine the impact of them in a game theoretic model such as the one developed here. It could also be discussed if the external funding in the payoff functions should instead be defined as a percentage of investment costs. Furthermore, if affordability should be the only award criterion linked directly to CEF-E funding, as suggested by Schittekatte et al. (2021) and mentioned in section 4.2.1.1, the payoff functions should take into account that external funding is only paid when the energy consumers cannot afford to pay for the investments. However, how to do this in practice is a complicated matter.

Although there are some limitations of using evolutionary game theory, a strength is the assumption that the various players are not fully rational and that they can learn during the game. Hence, the model is in this way more realistic than many other economic models. However, another weakness is the lack of empirical testing as also mentioned by Faber and Frenken (2009) with the exception of the numerical simulations conducted in section 5.3. This weakness could be coped with, though, by testing the significance of the parameters in the model using econometric methods as is done by, for example, Tang et al. (2021), as mentioned in section 2.3, who set up a panel model for testing the impact of the parameters in the evolutionary game model. However, for the game studied in this thesis, this would require a bigger job of gathering data on several parameters associated with great uncertainty or sensitivity, such as the size of cost reductions, which is often, to a smaller or greater extent, the firm's private information as mentioned in chapter 2. It could also be interesting to extend the analysis by conducting numerical simulations for the parameters taken as given to, for example, study the impact of costs of changing regulations or imposing penalties on convergence to the stable state. As mentioned in section 2.3, Sheng et al. (2020) find the ratio of supervision costs and penalties to affect the central government's willingness to implement supervision. Furthermore, it could be interesting to investigate the impact of a change in the size of cost reductions or investment costs on the convergence to the ESS.

Chapter 7

Conclusion

Through the European Green Deal, which the European Commission presented in December 2019, the EU has set a goal to become the first climate-neutral continent by 2050 (European Commission, n.d.-a). This goal became legally binding with the adoption of the European Climate Law in July 2021 (European Commission, n.d.-d). Since the energy sector is responsible for about 75% of greenhouse gas emissions in the EU, decarbonizing the sector is essential for achieving the goals of the European Green Deal (European Commission, n.d.-c). It is widely recognized in the academic literature that innovation is key to achieving the green transition, but the energy sector, and especially energy networks, lack innovation (Jamasb et al., 2020; Poudineh et al., 2020; Rong et al., 2022). In order to investigate how to overcome this challenge, I have posed the following research question: *How can energy networks in the European Union be encouraged to increase innovation with decarbonization goals?* In order to analyse this question, I use a tripartite evolutionary game model. By doing so, I both contribute to the area of research that studies how to induce energy networks in the EU to increase innovation with the aim of decarbonizing the energy sector and the research area that uses evolutionary game theory for examining how to improve environmental regulation and achieving green transition.

The three groups of players in the game are the Commission, the national regulators and the energy networks. They can each choose to play a cooperation strategy or a non-cooperation strategy. The cooperation strategy of the Commission is to change its legislation in order to induce innovation with decarbonization goals in energy networks. This, for example, involves changing the TEN-E Regulation to make it more compatible with the decarbonization goals of the European Green Deal, as suggested by Schittekatte et al. (2021). Since a revision of the TEN-E Regulation with this objective has already begun, the initial probability of the Commission in the game, i.e. the initial probability that it will choose its cooperative strategy, is assumed to be relatively high.

The cooperation strategy of the regulators is to change to a combination of an input-based and output-based regulatory mechanism. This is thought to, through the input-based mechanism, encourage investments in innovation with decarbonization goals by first of all accounting for the increased risk profile that projects of this kind often have and second of all, through the output-based mechanism, incentivizing improved outcome by sharing a fraction of a possible cost reduction from the innovation with the energy networks (Poudineh et al., 2020). This latter mechanism deals with the moral hazard issue of the regulators not being able to observe the efficiency of the energy networks. The non-cooperation strategy of the regulators is to keep using a cost-based mechanism, which does not provide incentives for innovation and might lead to the energy networks misreporting their costs, or an incentive-based mechanism that incentivizes cost-efficiency. Since these two kinds of regulatory mechanisms are what most regulators use at the moment (Haffner et al., 2019; Jamasb et al., 2020), the initial probability that regulators choose their cooperation strategy is assumed to be low.

In accordance with the objective of the game being to analyse how to induce energy networks to increase innovation with the aim of decarbonizing the energy sector, the cooperation strategy of the energy networks is to invest in innovation with decarbonization goals. The non-cooperation strategy of the energy networks is to not invest. Since the energy sector, and energy networks in particular, lack innovation as mentioned above, the initial probability that energy networks choose their cooperation strategy is also assumed to be low. Four different cases of the game are analysed. The first case is as outlined above. In case 2 and case 4, it is additionally assumed that the Commission can penalize the regulators for not cooperating, given that the Commission cooperates. In case 3 and case 4, non-cooperation from the Commission is assumed to contradict the European Climate Law and result in a penalty imposed on the Commission.

In order to derive the equilibrium points of the game, first, the expected payoffs of choosing the cooperation and non-cooperation strategies, respectively, plus the average expected payoffs of the three groups of players in the four cases of the game are derived. Then, the replicator dynamics equations are calculated and set equal to zero in order to derive the equilibrium points of the game. By doing so, it is evident that each of the four cases of the game have eight equilibrium points, $E(x, y, z)$, in pure strategies: $E_1(0, 0, 0)$, $E_2(1, 0, 0)$, $E_3(0, 1, 0)$, $E_4(0, 0, 1)$, $E_5(1, 1, 0)$, $E_6(1, 0, 1)$, $E_7(0, 1, 1)$ and $E_8(1, 1, 1)$. A stability analysis of each point in each of the four cases is conducted using the Jacobian matrix since a necessary and sufficient condition for determining whether an equilibrium point is asymptotically stable, and hence whether it is an ESS, is that all eigenvalues of the Jacobian matrix must be negative (Shan & Yang, 2019). The only point which is found to be an ESS is the equilibrium point $E_8(1, 1, 1)$, indicating cooperation of the three groups of players, in case 4. However, for this point to be stable, two conditions must be met. These conditions imply that the penalties imposed on the Commission and the regulators, respectively, in case they do not choose to cooperate must be greater than the expected decrease in payoffs they will have from choosing cooperation over non-cooperation, given that the strategies of the other groups of players are fixed.

Sensitivity analyses are conducted for the parameters in the model that are assumed to be determined through policies, given that the Commission and the regulators choose their cooperation strategies. However, it is argued that one of these parameters, namely the size of the penalty imposed on the Commission in case it does not cooperate, is probably exogenous in the model. In addition to this, sensitivity analyses for the initial probabilities of cooperation from the three groups of players are conducted. It is found that a high initial probability of cooperation from the Commission increases the convergence rate for the regulators and energy networks to the stable state, given their initial probabilities are low. Furthermore, since it is assumed that the initial probability of the Commission is high while the initial probabilities of the regulators and energy networks are assumed to be low, as mentioned above, it seems reasonable for the Commission to increase the probability of external funding for the energy networks, which is implied from the sensitivity analyses to increase the convergence rate of the energy networks to the stable state, and increase the penalty imposed on regulators for not cooperating, which seems to increase the convergence rate of both the regulators and the energy networks. The importance of the cooperation of a higher authority that has the power to subsidize and penalize the remaining players of the game is supported by findings of, for example, Yang et al. (2021) and Guo et al. (2021).

A strength of using evolutionary game theory is that the players are assumed to be boundedly rational, which contrasts with the full rationality assumption of traditional game theory, and that they are assumed to be able to learn over time and adjust their strategies accordingly. On the other hand, a limitation of the model is the great uncertainty associated with the way payoffs are calculated and the lack of empirical testing with the exception of the numerical simulations. However, this latter limitation can be dealt with by testing the evolutionary game model using econometric methods, as is done by Tang et al. (2021). Another possible extension of or different take on the analysis is to model the Commission as a social welfare-maximizing social planner, resembling the method used by Cantner and Kuhn (1999) and Rong et al. (2022).

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Appendix A

Appendix: Replicator Dynamics Equations

A.1 Case 1

Expected payoff of the Commission from cooperation:

$$\begin{aligned}\pi_{EC1-C} &= y\big[z\big(\pi_{EC1-1}\big)+\big(1-z\big)\big(\pi_{EC1-2}\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(\pi_{EC1-3}\big)+\big(1-z\big)\big(\pi_{EC1-5}\big)\big] \\ &= y\big[z\big(E_1-\alpha_1\ F-c_1\big)+\big(1-z\big)\big(-E_2-c_1\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(E_1-\alpha_1 F-c_1\big)+\big(1-z\big)\big(-E_2-c_1\big)\big] \\ &= z\big(E_1+E_2-\alpha_1 F\big)-E_2-c_1\end{aligned} \tag{A.1}$$

Expected payoff of the Commission from non-cooperation:

$$\begin{aligned}\pi_{EC1-N} &= y\big[z\big(\pi_{EC1-4}\big)+\big(1-z\big)\big(\pi_{EC1-6}\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(\pi_{EC1-7}\big)+\big(1-z\big)\big(\pi_{EC1-8}\big)\big] \\ &= y\big[z\big(E_1-\alpha_2 F\big)+\big(1-z\big)\big(-E_2\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(E_1-\alpha_2 F\big)+\big(1-z\big)\big(-E_2\big)\big] \\ &= z\big(E_1+E_2-\alpha_2 F\big)-E_2\end{aligned} \tag{A.2}$$

Average expected payoff of the Commission:

$$\begin{aligned}\bar{\pi}_{EC1} &= x\big(\pi_{EC1-C}\big)+\big(1-x\big)\big(\pi_{EC1-N}\big) \\ &= x\big[z\big(E_1+E_2-\alpha_1 F\big)-E_2-c_1\big]+\big(1-x\big)\big[z\big(E_1+E_2-\alpha_2 F\big)-E_2\big] \\ &= z\big(E_1+E_2\big)-E_2-xc_1-zF\big[x\alpha_1+\big(1-x\big)\alpha_2\big]\end{aligned} \tag{A.3}$$

Expected payoff of the regulators from cooperation:

$$\begin{aligned}\pi_{R1-C} &= x\big[z\big(\pi_{R1-1}\big) + \big(1-z\big)\big(\pi_{R1-2}\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(\pi_{R1-4}\big) + \big(1-z\big)\big(\pi_{R1-6}\big)\big] \\ &= x\big[z\big((1-\beta)s - I - c_3\big) + \big(1-z\big)\big(-c_3\big)\big] \\ &\quad + \big(1-x\big)\big[z\big((1-\beta)s - I - c_3\big) + \big(1-z\big)\big(-c_3\big)\big] \\ &= z\big((1-\beta)s - I\big) - c_3\end{aligned} \tag{A.4}$$

Expected payoff of the regulators from non-cooperation:

$$\begin{aligned}\pi_{R1-N} &= x\big[z\big(\pi_{R1-3}\big) + \big(1-z\big)\big(\pi_{R1-5}\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(\pi_{R1-7}\big) + \big(1-z\big)\big(\pi_{R1-8}\big)\big] \\ &= x\big[z\big(s\big) + \big(1-z\big)\big(0\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(s\big) + \big(1-z\big)\big(0\big)\big] \\ &= zs\end{aligned} \tag{A.5}$$

Average expected payoff of the regulators:

$$\begin{aligned}\bar{\pi}_{R1} &= y\big(\pi_{R1-C}\big) + \big(1-y\big)\big(\pi_{R1-N}\big) \\ &= y\big[z\big((1-\beta)s - I\big) - c_3\big] + \big(1-y\big)\big[zs\big] \\ &= zs - y\big[z\big(\beta s + I\big) + c_3\big]\end{aligned} \tag{A.6}$$

Expected payoff of the energy networks from cooperation:

$$\begin{aligned}\pi_{EN1-C} &= x\big[y\big(\pi_{EN1-1}\big) + \big(1-y\big)\big(\pi_{EN1-3}\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN1-4}\big) + \big(1-y\big)\big(\pi_{EN1-7}\big)\big] \\ &= x\big[y\big(\alpha_1 F + \beta s\big) + \big(1-y\big)\big(\alpha_1 F - I\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\alpha_2 F + \beta s\big) + \big(1-y\big)\big(\alpha_2 F - I\big)\big] \\ &= y\big(\beta s + I\big) - I + \big(x\alpha_1 + (1-x)\alpha_2\big)F\end{aligned} \tag{A.7}$$

Expected payoff of the energy networks from non-cooperation:

$$\begin{aligned}\pi_{EN1-N} &= x\big[y\big(\pi_{EN1-2}\big) + \big(1-y\big)\big(\pi_{EN1-5}\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN1-6}\big) + \big(1-y\big)\big(\pi_{EN1-8}\big)\big] \\ &= x\big[y\big(0\big) + \big(1-y\big)\big(0\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(0\big) + \big(1-y\big)\big(0\big)\big] \\ &= 0\end{aligned} \tag{A.8}$$

Average expected payoff of the energy networks:

$$\begin{aligned}\bar{\pi}_{EN1} &= z\big(\pi_{EN1-C}\big) + \big(1-z\big)\big(\pi_{EN1-N}\big) \\ &= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big] + \big(1-z\big)\big[0\big] \\ &= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]\end{aligned} \tag{A.9}$$

Then the replicator dynamics equations can be set up. Replicator dynamics equation of the Commission:

$$\begin{aligned}F\big(x\big)_1 = \frac{dx}{dt} &= x\big(\pi_{EC1-C} - \bar{\pi}_{EC1}\big) \\ &= x\big[z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 \\ &\quad - \big(z\big(E_1 + E_2\big) - xc_1 - E_2 - zF\big[x\alpha_1 + \big(1-x\big)\alpha_2\big]\big)\big] \\ &= x\big(1-x\big)\big[zF\big(\alpha_2 - \alpha_1\big) - c_1\big]\end{aligned} \tag{A.10}$$

Replicator dynamics equation of the regulators:

$$\begin{aligned}F\big(y\big)_1 = \frac{dy}{dt} &= y\big(\pi_{R1-C} - \bar{\pi}_{R1}\big) \\ &= y\big[z\big(\big(1-\beta\big)s - I\big) - c_3 - \big(zs - y\big[z\big(\beta s + I\big) + c_3\big]\big)\big] \\ &= y\big(1-y\big)\big[-z\big(\beta s + I\big) - c_3\big]\end{aligned} \tag{A.11}$$

Replicator dynamics equation of the energy networks:

$$\begin{aligned}F\big(z\big)_1 = \frac{dz}{dt} &= z\big(\pi_{EN1-C} - \bar{\pi}_{EN1}\big) \\ &= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F \\ &\quad - \big(z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]\big)\big] \\ &= z\big(1-z\big)\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]\end{aligned} \tag{A.12}$$

A.2 Case 2

Expected payoff of the Commission from cooperation:

$$\begin{aligned}\pi_{EC2-C} &= y\big[z\big(\pi_{EC2-1}\big) + \big(1-z\big)\big(\pi_{EC2-2}\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(\pi_{EC2-3}\big) + \big(1-z\big)\big(\pi_{EC2-5}\big)\big] \\ &= y\big[z\big(E_1 - \alpha_1 F - c_1\big) + \big(1-z\big)\big(-E_2 - c_1\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(E_1 - \alpha_1 F - c_1 - c_2\big) + \big(1-z\big)\big(-E_2 - c_1 - c_2\big)\big] \\ &= z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 - \big(1-y\big)c_2\end{aligned} \tag{A.13}$$

Expected payoff of the Commission from non-cooperation:

$$\begin{aligned}\pi_{EC2-N} &= y\big[z\big(\pi_{EC2-4}\big) + \big(1-z\big)\big(\pi_{EC2-6}\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(\pi_{EC2-7}\big) + \big(1-z\big)\big(\pi_{EC2-8}\big)\big] \\ &= y\big[z\big(E_1 - \alpha_2 F\big) + \big(1-z\big)\big(-E_2\big)\big] \\ &\quad + \big(1-y\big)\big[z\big(E_1 - \alpha_2 F\big) + \big(1-z\big)\big(-E_2\big)\big] \\ &= z\big(E_1 + E_2 - \alpha_2 F\big) - E_2\end{aligned} \tag{A.14}$$

Average expected payoff of the Commission:

$$\begin{aligned}\bar{\pi}_{EC2} &= x\big(\pi_{EC2-C}\big) + \big(1-x\big)\big(\pi_{EC2-N}\big) \\ &= x\big[z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 - \big(1-y\big)c_2\big] \\ &\quad + \big(1-x\big)\big[z\big(E_1 + E_2 - \alpha_2 F\big) - E_2\big] \\ &= z\big(E_1 + E_2\big) - E_2 - x\big[c_1 + \big(1-y\big)c_2\big] - zF\big(x\alpha_1 + \big(1-x\big)\alpha_2\big)\end{aligned} \tag{A.15}$$

Expected payoff of the regulators from cooperation:

$$\begin{aligned}\pi_{R2-C} &= x\big[z\big(\pi_{R2-1}\big) + \big(1-z\big)\big(\pi_{R2-2}\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(\pi_{R2-4}\big) + \big(1-z\big)\big(\pi_{R2-6}\big)\big] \\ &= x\big[z\big(\big(1-\beta\big)s - I - c_3\big) + \big(1-z\big)\big(-c_3\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(\big(1-\beta\big)s - I - c_3\big) + \big(1-z\big)\big(-c_3\big)\big] \\ &= z\big(\big(1-\beta\big)s - I\big) - c_3\end{aligned} \tag{A.16}$$

Expected payoff of the regulators from non-cooperation:

$$\begin{aligned}\pi_{R2-N} &= x\big[z\big(\pi_{R2-3}\big) + \big(1-z\big)\big(\pi_{R2-5}\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(\pi_{R2-7}\big) + \big(1-z\big)\big(\pi_{R2-8}\big)\big] \\ &= x\big[z\big(s-p\big) + \big(1-z\big)\big(-p\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(s\big) + \big(1-z\big)\big(0\big)\big] \\ &= zs - xp\end{aligned} \tag{A.17}$$

Average expected payoff of the regulators:

$$\begin{aligned}\bar{\pi}_{R2} &= y\big(\pi_{R2-C}\big) + \big(1-y\big)\big(\pi_{R2-N}\big) \\ &= y\big[z\big(\big(1-\beta\big)s - I\big) - c_3\big] + \big(1-y\big)\big[zs - xp\big] \\ &= zs - y\big[z\big(\beta s + I\big) + c_3\big] - \big(1-y\big)xp\end{aligned} \tag{A.18}$$

Expected payoff of the energy networks from cooperation:

$$\begin{aligned}\pi_{EN2-C} &= x\big[y\big(\pi_{EN2-1}\big) + \big(1-y\big)\big(\pi_{EN2-3}\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN2-4}\big) + \big(1-y\big)\big(\pi_{EN2-7}\big)\big] \\ &= x\big[y\big(\alpha_1 F + \beta s\big) + \big(1-y\big)\big(\alpha_1 F - I\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\alpha_2 F + \beta s\big) + \big(1-y\big)\big(\alpha_2 F - I\big)\big] \\ &= y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\end{aligned} \tag{A.19}$$

Expected payoff of the energy networks from non-cooperation:

$$\begin{aligned}\pi_{EN2-N} &= x\big[y\big(\pi_{EN1-2}\big) + \big(1-y\big)\big(\pi_{EN2-5}\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN2-6}\big) + \big(1-y\big)\big(\pi_{EN2-8}\big)\big] \\ &= x\big[y\big(0\big) + \big(1-y\big)\big(0\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(0\big) + \big(1-y\big)\big(0\big)\big] \\ &= 0\end{aligned} \tag{A.20}$$

Average expected payoff of the energy networks:

$$\begin{aligned}\bar{\pi}_{EN2} &= z\big(\pi_{EN2-C}\big) + \big(1-z\big)\big(\pi_{EN2-N}\big) \\ &= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big] + \big(1-z\big)\big[0\big] \\ &= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]\end{aligned} \tag{A.21}$$

Then the replicator dynamics equations can be set up. Replicator dynamics equation for the cooperation strategy of the Commission:

$$\begin{aligned}F\big(x\big)_2 &= \frac{dx}{dt} = x\big(\pi_{EC2-C} - \bar{\pi}_{EC2}\big) \\ &= x\big[z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 - \big(1-y\big)c_2 \\ &\quad - \big(z\big(E_1 + E_2\big) - E_2 - x\big[c_1 + \big(1-y\big)c_2\big] - zF\big(x\alpha_1 + \big(1-x\big)\alpha_2\big)\big)\big] \\ &= x\big(1-x\big)\big[zF\big(\alpha_2 - \alpha_1\big) - c_1 - \big(1-y\big)c_2\big]\end{aligned} \tag{A.22}$$

Replicator dynamics equation for the cooperation strategy of the regulators:

$$\begin{aligned}F\big(y\big)_2 &= \frac{dy}{dt} = y\big(\pi_{R2-C} - \bar{\pi}_{R2}\big) \\ &= y\big[z\big(\big(1-\beta\big)s - I\big) - c_3 - \big(zs - y\big[z\big(\beta s + I\big) + c_3\big] - \big(1-y\big)xp\big)\big] \\ &= y\big(1-y\big)\big[xp - z\big(\beta s + I\big) - c_3\big]\end{aligned} \tag{A.23}$$

Replicator dynamics equation for the cooperation strategy of the energy networks:

$$\begin{aligned} F(z)_2 = \frac{dz}{dt} &= z\big(\pi_{EN2-C} - \bar{\pi}_{EN2}\big) \\ &= z\big[y(\beta s + I) - I + \big(x\alpha_1 + (1-x)\alpha_2\big)F \\ &\quad - \big(z\big[y(\beta s + I) - I + \big(x\alpha_1 + (1-x)\alpha_2\big)F\big]\big)\big] \\ &= z(1-z)\big[y(\beta s + I) - I + \big(x\alpha_1 + (1-x)\alpha_2\big)F\big] \end{aligned} \tag{A.24}$$

A.3 Case 3

Expected payoff of the Commission from cooperation:

$$\begin{aligned} \pi_{EC3-C} &= y\big[z(\pi_{EC3-1}) + (1-z)(\pi_{EC3-2})\big] \\ &\quad + (1-y)\big[z(\pi_{EC3-3}) + (1-z)(\pi_{EC3-5})\big] \\ &= y\big[z(E_1 - \alpha_1\ F - c_1) + (1-z)(-E_2 - c_1)\big] \\ &\quad + (1-y)\big[z(E_1 - \alpha_1 F - c_1) + (1-z)(-E_2 - c_1)\big] \\ &= z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 \end{aligned} \tag{A.25}$$

Expected payoff of the Commission from non-cooperation:

$$\begin{aligned} \pi_{EC3-N} &= y\big[z(\pi_{EC3-4}) + (1-z)(\pi_{EC3-6})\big] \\ &\quad + (1-y)\big[z(\pi_{EC3-7}) + (1-z)(\pi_{EC3-8})\big] \\ &= y\big[z(E_1 - \alpha_2 F - q) + (1-z)(-E_2 - q)\big] \\ &\quad + (1-y)\big[z(E_1 - \alpha_2 F - q) + (1-z)(-E_2 - q)\big] \\ &= z\big(E_1 + E_2 - \alpha_2 F\big) - E_2 - q \end{aligned} \tag{A.26}$$

Average expected payoff of the Commission:

$$\begin{aligned} \bar{\pi}_{EC3} &= x(\pi_{EC3-C}) + (1-x)(\pi_{EC3-N}) \\ &= x\big[z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1\big] + (1-x)\big[z\big(E_1 + E_2 - \alpha_2 F\big) - E_2 - q\big] \\ &= z(E_1 + E_2) - E_2 - \mathrm{xc}_1 - (1-x)q - zF\big(x\alpha_1 + (1-x)\alpha_2\big) \end{aligned} \tag{A.27}$$

Expected payoff of the regulators from cooperation:

$$\begin{aligned} \pi_{R3-C} &= x\big[z(\pi_{R3-1}) + (1-z)(\pi_{R3-2})\big] \\ &\quad + (1-x)\big[z(\pi_{R3-4}) + (1-z)(\pi_{R3-6})\big] \\ &= x\big[z\big((1-\beta)s - I - c_3\big) + (1-z)(-c_3)\big] \\ &\quad + (1-x)\big[z\big((1-\beta)s - I - c_3\big) + (1-z)(-c_3)\big] \\ &= z\big((1-\beta)s - I\big) - c_3 \end{aligned} \tag{A.28}$$

Expected payoff of the regulators from non-cooperation:

$$\begin{aligned}\pi_{R3-N} &= x\big[z\big(\pi_{R3-3}\big) + \big(1-z\big)\big(\pi_{R3-5}\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(\pi_{R3-7}\big) + \big(1-z\big)\big(\pi_{R3-8}\big)\big] \\ &= x\big[z\big(s\big) + \big(1-z\big)\big(0\big)\big] \\ &\quad + \big(1-x\big)\big[z\big(s\big) + \big(1-z\big)\big(0\big)\big] \\ &= zs\end{aligned} \tag{A.29}$$

Average expected payoff of the regulators:

$$\begin{aligned}\bar{\pi}_{R3} &= y\big(\pi_{R3-C}\big) + \big(1-y\big)\big(\pi_{R3-N}\big) \\ &= y\big[z\big((1-\beta)s - I\big) - c_3\big] + \big(1-y\big)\big[zs\big] \\ &= zs - y\big[z\big(\beta s + I\big) + c_3\big]\end{aligned} \tag{A.30}$$

Expected payoff of the energy networks from cooperation:

$$\begin{aligned}\pi_{EN3-C} &= x\big[y\big(\pi_{EN3-1}\big) + \big(1-y\big)\big(\pi_{EN3-3}\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN3-4}\big) + \big(1-y\big)\big(\pi_{EN3-7}\big)\big] \\ &= x\big[y\big(\alpha_1 F + \beta s\big) + \big(1-y\big)\big(\alpha_1 F - I\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\alpha_2 F + \beta s\big) + \big(1-y\big)\big(\alpha_2 F - I\big)\big] \\ &= y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\end{aligned} \tag{A.31}$$

Expected payoff of the energy networks from non-cooperation:

$$\begin{aligned}\pi_{EN3-N} &= x\big[y\big(\pi_{EN3-2}\big) + \big(1-y\big)\big(\pi_{EN3-5}\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN3-6}\big) + \big(1-y\big)\big(\pi_{EN3-8}\big)\big] \\ &= x\big[y\big(0\big) + \big(1-y\big)\big(0\big)\big] \\ &\quad + \big(1-x\big)\big[y\big(0\big) + \big(1-y\big)\big(0\big)\big] \\ &= 0\end{aligned} \tag{A.32}$$

Average expected payoff of the energy networks:

$$\begin{aligned}\bar{\pi}_{EN3} &= z\big(\pi_{EN3-C}\big) + \big(1-z\big)\big(\pi_{EN3-N}\big) \\ &= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big] + \big(1-z\big)\big[0\big] \\ &= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]\end{aligned} \tag{A.33}$$

Then the replicator dynamics equations can be set up. Replicator dynamics equation for the cooperation strategy of the Commission:

$$\begin{aligned}F(x)_3 &= \frac{dx}{dt} = x(\pi_{EC3-C} - \bar{\pi}_{EC3}) \\ &= x\big[z(E_1 + E_2 - \alpha_1 F) - E_2 - c_1 \\ &\quad - \big(z(E_1 + E_2) - zF(x\alpha_1 + (1-x)\alpha_2) - E_2 - \mathrm{xc}_1 - (1-x)q\big)\big] \\ &= x(1-x)\big[zF(\alpha_2 - \alpha_1) - c_1 + q\big]\end{aligned} \tag{A.34}$$

Replicator dynamics equation for the cooperation strategy of the regulators:

$$\begin{aligned}F(y)_3 &= \frac{dy}{dt} = y(\pi_{R3-C} - \bar{\pi}_{R3}) \\ &= y\big[z((1-\beta)s - I) - c_3 - \big(zs - y\big[z(\beta s + I) + c_3\big]\big)\big] \\ &= y(1-y)\big[-z(\beta s + I) - c_3\big]\end{aligned} \tag{A.35}$$

Replicator dynamics equation for the cooperation strategy of the energy networks:

$$\begin{aligned}F(z)_3 &= \frac{dz}{dt} = z(\pi_{EN3-C} - \bar{\pi}_{EN3}) \\ &= z\big[y(\beta s + I) - I + (x\alpha_1 + (1-x)\alpha_2)F \\ &\quad - \big(z\big[y(\beta s + I) - I + (x\alpha_1 + (1-x)\alpha_2)F\big]\big)\big] \\ &= z(1-z)\big[y(\beta s + I) - I + (x\alpha_1 + (1-x)\alpha_2)F\big]\end{aligned} \tag{A.36}$$

A.4 Case 4

Expected payoff of the Commission from cooperation:

$$\begin{aligned}\pi_{EC4-C} &= y\big[z(\pi_{EC4-1}) + (1-z)(\pi_{EC4-2})\big] \\ &\quad + (1-y)\big[z(\pi_{EC4-3}) + (1-z)(\pi_{EC4-5})\big] \\ &= y\big[z(E_1 - \alpha_1\ F - c_1) + (1-z)(-E_2 - c_1)\big] \\ &\quad + (1-y)\big[z(E_1 - \alpha_1 F - c_1 - c_2) + (1-z)(-E_2 - c_1 - c_2)\big] \\ &= z(E_1 + E_2 - \alpha_1 F) - E_2 - c_1 - (1-y)c_2\end{aligned} \tag{A.37}$$

Expected payoff of the Commission from non-cooperation:

$$\begin{aligned}\pi_{EC4-N} &= y\big[z(\pi_{EC4-4}) + (1-z)(\pi_{EC4-6})\big] \\ &\quad + (1-y)\big[z(\pi_{EC4-7}) + (1-z)(\pi_{EC4-8})\big] \\ &= y\big[z(E_1 - \alpha_2 F - q) + (1-z)(-E_2 - q)\big] \\ &\quad + (1-y)\big[z(E_1 - \alpha_2 F - q) + (1-z)(-E_2 - q)\big] \\ &= z(E_1 + E_2 - \alpha_2 F) - E_2 - q\end{aligned} \tag{A.38}$$

Average expected payoff of the Commission:

$$\begin{aligned}\bar{\pi}_{EC4} &= x\big(\pi_{EC4-C}\big) + \big(1-x\big)\big(\pi_{EC4-N}\big)\\ &= x\big[z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 - \big(1-y\big)c_2\big]\\ &\quad + \big(1-x\big)\big[z\big(E_1 + E_2 - \alpha_2 F\big) - E_2 - q\big]\\ &= z\big(E_1 + E_2\big) - E_2 - x\big(c_1 + \big(1-y\big)c_2\big) - \big(1-x\big)q - zF\big(x\alpha_1 + \big(1-x\big)\alpha_2\big)\end{aligned} \tag{A.39}$$

Expected payoff of the regulators from cooperation:

$$\begin{aligned}\pi_{R4-C} &= x\big[z\big(\pi_{R4-1}\big) + \big(1-z\big)\big(\pi_{R4-2}\big)\big]\\ &\quad + \big(1-x\big)\big[z\big(\pi_{R4-4}\big) + \big(1-z\big)\big(\pi_{R4-6}\big)\big]\\ &= x\big[z\big(\big(1-\beta\big)s - I - c_3\big) + \big(1-z\big)\big(-c_3\big)\big]\\ &\quad + \big(1-x\big)\big[z\big(\big(1-\beta\big)s - I - c_3\big) + \big(1-z\big)\big(-c_3\big)\big]\\ &= z\big(\big(1-\beta\big)s - I\big) - c_3\end{aligned} \tag{A.40}$$

Expected payoff of the regulators from non-cooperation:

$$\begin{aligned}\pi_{R4-N} &= x\big[z\big(\pi_{R4-3}\big) + \big(1-z\big)\big(\pi_{R4-5}\big)\big]\\ &\quad + \big(1-x\big)\big[z\big(\pi_{R4-7}\big) + \big(1-z\big)\big(\pi_{R4-8}\big)\big]\\ &= x\big[z\big(s-p\big) + \big(1-z\big)\big(-p\big)\big]\\ &\quad + \big(1-x\big)\big[z\big(s\big) + \big(1-z\big)\big(0\big)\big]\\ &= zs - xp\end{aligned} \tag{A.41}$$

Average expected payoff of the regulators:

$$\begin{aligned}\bar{\pi}_{R4} &= y\big(\pi_{R4-C}\big) + \big(1-y\big)\big(\pi_{R4-N}\big)\\ &= y\big[z\big(\big(1-\beta\big)s - I\big) - c_3\big] + \big(1-y\big)\big[zs - xp\big]\\ &= zs - y\big[z\big(\beta s + I\big) + c_3\big] - \big(1-y\big)xp\end{aligned} \tag{A.42}$$

Expected payoff of the energy networks from cooperation:

$$\begin{aligned}\pi_{EN4-C} &= x\big[y\big(\pi_{EN4-1}\big) + \big(1-y\big)\big(\pi_{EN4-3}\big)\big]\\ &\quad + \big(1-x\big)\big[y\big(\pi_{EN4-4}\big) + \big(1-y\big)\big(\pi_{EN4-7}\big)\big]\\ &= x\big[y\big(\alpha_1 F + \beta s\big) + \big(1-y\big)\big(\alpha_1 F - I\big)\big]\\ &\quad + \big(1-x\big)\big[y\big(\alpha_2 F + \beta s\big) + \big(1-y\big)\big(\alpha_2 F - I\big)\big]\\ &= y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\end{aligned} \tag{A.43}$$

Expected payoff of the energy networks from non-cooperation:

$$\begin{aligned}
\pi_{EN4-N} &= x\big[y\big(\pi_{EN4-2}\big) + \big(1-y\big)\big(\pi_{EN4-5}\big)\big] \\
&\quad + \big(1-x\big)\big[y\big(\pi_{EN4-6}\big) + \big(1-y\big)\big(\pi_{EN4-8}\big)\big] \\
&= x\big[y\big(0\big) + \big(1-y\big)\big(0\big)\big] \\
&\quad + \big(1-x\big)\big[y\big(0\big) + \big(1-y\big)\big(0\big)\big] \\
&= 0
\end{aligned} \tag{A.44}$$

Average expected payoff of the energy networks:

$$\begin{aligned}
\bar{\pi}_{EN4} &= z\big(\pi_{EN4-C}\big) + \big(1-z\big)\big(\pi_{EN4-N}\big) \\
&= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big] + \big(1-z\big)\big[0\big] \\
&= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]
\end{aligned} \tag{A.45}$$

Then the replicator dynamics equations can be set up. Replicator dynamics equation for the cooperation strategy of the Commission:

$$\begin{aligned}
F\big(x\big)_4 &= \frac{dx}{dt} = x\big(\pi_{EC4-C} - \bar{\pi}_{EC4}\big) \\
&= x\big[z\big(E_1 + E_2 - \alpha_1 F\big) - E_2 - c_1 - \big(1-y\big)c_2 \\
&\quad - \big(z\big(E_1 + E_2\big) - E_2 - x\big(c_1 + \big(1-y\big)c_2\big) - \big(1-x\big)q - zF\big(x\alpha_1 + \big(1-x\big)\alpha_2\big)\big)\big] \\
&= x\big(1-x\big)\big[zF\big(\alpha_2 - \alpha_1\big) - c_1 - \big(1-y\big)c_2 + q\big]
\end{aligned} \tag{A.46}$$

Replicator dynamics equation for the cooperation strategy of the regulators:

$$\begin{aligned}
F\big(y\big)_4 &= \frac{dy}{dt} = y\big(\pi_{R4-C} - \bar{\pi}_{R4}\big) \\
&= y\big[z\big(\big(1-\beta\big)s - I\big) - c_3 - \big(zs - y\big[z\big(\beta s + I\big) + c_3\big] - \big(1-y\big)xp\big)\big] \\
&= y\big(1-y\big)\big[xp - z\big(\beta s + I\big) - c_3\big]
\end{aligned} \tag{A.47}$$

Replicator dynamics equation for the cooperation strategy of the energy networks:

$$\begin{aligned}
F\big(z\big)_4 &= \frac{dz}{dt} = z\big(\pi_{EN1-C} - \bar{\pi}_{EN1}\big) \\
&= z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F \\
&\quad - \big(z\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]\big)\big] \\
&= z\big(1-z\big)\big[y\big(\beta s + I\big) - I + \big(x\alpha_1 + \big(1-x\big)\alpha_2\big)F\big]
\end{aligned} \tag{A.48}$$

Appendix B

Appendix: Stability Analysis

B.1 Case 1

The nine inputs in the Jacobian matrix are calculated:

$$\frac{\partial F(x)_1}{\partial x} = (1-2x)\left[zF(\alpha_2-\alpha_1)-c_1\right] \tag{B.1}$$

$$\frac{\partial F(x)_1}{\partial y} = 0 \tag{B.2}$$

$$\frac{\partial F(x)_1}{\partial z} = x(1-x)F(\alpha_2-\alpha_1) \tag{B.3}$$

$$\frac{\partial F(y)_1}{\partial x} = 0 \tag{B.4}$$

$$\frac{\partial F(y)_1}{\partial y} = (1-2y)\left[-z(\beta s+I)-c_3\right] \tag{B.5}$$

$$\frac{\partial F(y)_1}{\partial z} = -y(1-y)(\beta s+I) \tag{B.6}$$

$$\frac{\partial F(z)_1}{\partial x} = z(1-z)(\alpha_1-\alpha_2)F \tag{B.7}$$

$$\frac{\partial F(z)_1}{\partial y} = z(1-z)(\beta s+I) \tag{B.8}$$

$$\frac{\partial F(z)_1}{\partial z} = (1-2z)\left[y(\beta s+I)-I+(x\alpha_1+(1-x)\alpha_2)F\right] \tag{B.9}$$

The following is true for all eight equilibrium points:

$$\frac{\partial F(x)}{\partial y} = \frac{\partial F(x)}{\partial z} = \frac{\partial F(y)}{\partial x} = \frac{\partial F(y)}{\partial z} = \frac{\partial F(z)}{\partial x} = \frac{\partial F(z)}{\partial y} = 0$$

Thus, the Jacobian matrix simplifies to:

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & 0 & 0 \\ 0 & \frac{\partial F(y)}{\partial y} & 0 \\ 0 & 0 & \frac{\partial F(z)}{\partial z} \end{bmatrix} \tag{B.10}$$

$\mathbf{E_4(0,0,1)}$

$$\begin{aligned} \frac{\partial F(x)_1}{\partial x} &= (1-2\times 0)\left[1\times F(\alpha_2-\alpha_1)-c_1\right] \\ &= F(\alpha_2-\alpha_1)-c_1<0 \end{aligned} \tag{B.11}$$

This always holds.

$$\begin{aligned} \frac{\partial F(y)_1}{\partial y} &= (1-2\times 0)\left[-1\times(\beta s+I)-c_3\right] \\ &= -\beta s-I-c_3<0 \end{aligned} \tag{B.12}$$

This always holds.

$$\begin{aligned} \frac{\partial F(z)_1}{\partial z} &= (1-2\times 1)\left[0\times(\beta s+I)-I+(0\times\alpha_1+(1-0)\,\alpha_2)\,F\right] \\ &= I-\alpha_2 F<0 \\ &\Leftrightarrow I<\alpha_2 F \end{aligned} \tag{B.13}$$

This must hold. **Not realistic.**

$\mathbf{E_6(1,0,1)}$

$$\begin{aligned} \frac{\partial F(x)_1}{\partial x} &= (1-2\times 1)\left[1\times F(\alpha_2-\alpha_1)-c_1\right] \\ &= -F(\alpha_2-\alpha_1)+c_1<0 \end{aligned} \tag{B.14}$$

This can never hold. **Unstable equilibrium.**

$$\begin{aligned} \frac{\partial F(y)_1}{\partial y} &= (1-2\times 0)\left[-1\times(\beta s+I)-c_3\right] \\ &= -\beta s-I-c_3<0 \end{aligned} \tag{B.15}$$

This always holds.

$$\begin{aligned} \frac{\partial F(z)_1}{\partial z} &= (1-2\times 1)\left[0\times(\beta s+I)-I+(1\times\alpha_1+(1-1)\,\alpha_2)\,F\right] \\ &= I-\alpha_1 F<0 \\ &\Leftrightarrow I<\alpha_1 F \end{aligned} \tag{B.16}$$

This must hold. **Not realistic.**

$\mathbf{E_7(0,1,1)}$

$$\begin{aligned}\frac{\partial F\left(x\right)_1}{\partial x}&=\left(1-2\times 0\right)\left[1\times F\left(\alpha_2-\alpha_1\right)-c_1\right]\\&=F\left(\alpha_2-\alpha_1\right)-c_1<0\end{aligned}\tag{B.17}$$

This always holds.

$$\begin{aligned}\frac{\partial F\left(y\right)_1}{\partial y}&=\left(1-2\times 1\right)\left[-1\times\left(\beta s+I\right)-c_3\right]\\&=\beta s+I+c_3<0\end{aligned}\tag{B.18}$$

This can never hold. **Unstable equilibrium.**

$$\begin{aligned}\frac{\partial F\left(z\right)_1}{\partial z}&=\left(1-2\times 1\right)\left[1\times\left(\beta s+I\right)-I+\left(0\times\alpha_1+\left(1-0\right)\alpha_2\right)F\right]\\&=-\beta s-\alpha_2 F<0\end{aligned}\tag{B.19}$$

This always holds.

$\mathbf{E_8(1,1,1)}$

$$\begin{aligned}\frac{\partial F\left(x\right)_1}{\partial x}&=\left(1-2\times 1\right)\left[1\times F\left(\alpha_2-\alpha_1\right)-c_1\right]\\&=-F\left(\alpha_2-\alpha_1\right)+c_1<0\end{aligned}\tag{B.20}$$

This can never hold. **Unstable equilibrium.**

$$\begin{aligned}\frac{\partial F\left(y\right)_1}{\partial y}&=\left(1-2\times 1\right)\left[-1\times\left(\beta s+I\right)-c_3\right]\\&=\beta s+I+c_3<0\end{aligned}\tag{B.21}$$

This can never hold. **Unstable equilibrium.**

$$\begin{aligned}\frac{\partial F\left(z\right)_1}{\partial z}&=\left(1-2\times 1\right)\left[1\times\left(\beta s+I\right)-I+\left(1\times\alpha_1+\left(1-1\right)\alpha_2\right)F\right]\\&=-\beta s-\alpha_1 F<0\end{aligned}\tag{B.22}$$

This always holds.

B.2 Case 2

The nine inputs in the Jacobian matrix:

$$\frac{\partial F\big(x\big)_2}{\partial x}=\big(1-2x\big)\big[zF\big(\alpha_2-\alpha_1\big)-c_1-\big(1-y\big)c_2\big]\tag{B.23}$$

$$\frac{\partial F(x)_2}{\partial y} = x(1-x)c_2 \tag{B.24}$$

$$\frac{\partial F(x)_2}{\partial z} = x(1-x)F(\alpha_2 - \alpha_1) \tag{B.25}$$

$$\frac{\partial F(y)_2}{\partial x} = y(1-y)p \tag{B.26}$$

$$\frac{\partial F(y)_2}{\partial y} = (1-2y)\left[xp - z(\beta s + I) - c_3\right] \tag{B.27}$$

$$\frac{\partial F(y)_2}{\partial z} = -y(1-y)(\beta s + I) \tag{B.28}$$

$$\frac{\partial F(z)_2}{\partial x} = z(1-z)(\alpha_1 - \alpha_2)F \tag{B.29}$$

$$\frac{\partial F(z)_2}{\partial y} = z(1-z)(\beta s + I) \tag{B.30}$$

$$\frac{\partial F(z)_2}{\partial z} = (1-2z)\left[y(\beta s + I) - I + (x\alpha_1 + (1-x)\alpha_2)F\right] \tag{B.31}$$

$\mathbf{E_4(0,0,1)}$

$$\begin{aligned}\frac{\partial F(x)_2}{\partial x} &= (1-2\times 0)\left[1\times F(\alpha_2-\alpha_1) - c_1 - (1-0)c_2\right]\\ &= F(\alpha_2-\alpha_1) - c_1 - c_2 < 0\end{aligned} \tag{B.32}$$

This always holds.

$$\begin{aligned}\frac{\partial F(y)_2}{\partial y} &= (1-2\times 0)\left[0\times p - 1\times(\beta s + I) - c_3\right]\\ &= -\beta s - I - c_3 < 0\end{aligned} \tag{B.33}$$

This always holds.

$$\begin{aligned}\frac{\partial F(z)_2}{\partial z} &= (1-2\times 1)\left[0\times(\beta s + I) - I + (0\times\alpha_1 + (1-0)\alpha_2)F\right]\\ &= I - \alpha_2 F < 0\\ &\Leftrightarrow I < \alpha_2 F\end{aligned} \tag{B.34}$$

This must hold. **Not realistic.**

$\mathbf{E_6(1,0,1)}$

$$\begin{aligned}\frac{\partial F(x)_2}{\partial x} &= (1-2\times 1)\left[1\times F(\alpha_2-\alpha_1) - c_1 - (1-0)c_2\right]\\ &= -F(\alpha_2-\alpha_1) + c_1 + c_2 < 0\end{aligned} \tag{B.35}$$

This can never hold. **Unstable equilibrium.**

$$\begin{aligned}\frac{\partial F(y)_2}{\partial y} &= (1-2\times 0)\left[1\times p - 1\times(\beta s + I) - c_3\right] \\ &= p - \beta s - I - c_3 < 0 \\ &\Leftrightarrow p < \beta s + I + c_3\end{aligned} \tag{B.36}$$

This must hold.

$$\begin{aligned}\frac{\partial F(z)_2}{\partial z} &= (1-2\times 1)\left[0\times(\beta s + I) - I + (1\times\alpha_1 + (1-1)\alpha_2)F\right] \\ &= I - \alpha_1 F < 0 \\ &\Leftrightarrow I < \alpha_1 F\end{aligned} \tag{B.37}$$

This must hold. **Not realistic.**

$\mathbf{E_7(0,1,1)}$

$$\begin{aligned}\frac{\partial F(x)_2}{\partial x} &= (1-2\times 0)\left[1\times F(\alpha_2-\alpha_1) - c_1 - (1-1)c_2\right] \\ &= F(\alpha_2-\alpha_1) - c_1 < 0\end{aligned} \tag{B.38}$$

This always holds.

$$\begin{aligned}\frac{\partial F(y)_2}{\partial y} &= (1-2\times 1)\left[0\times p - 1\times(\beta s + I) - c_3\right] \\ &= \beta s + I + c_3 < 0\end{aligned} \tag{B.39}$$

This can never hold. **Unstable equilibrium.**

$$\begin{aligned}\frac{\partial F(z)_2}{\partial z} &= (1-2\times 1)\left[1\times(\beta s + I) - I + (0\times\alpha_1 + (1-0)\alpha_2)F\right] \\ &= -\beta s - \alpha_2 F < 0\end{aligned} \tag{B.40}$$

This always holds.

$\mathbf{E_8(1,1,1)}$

$$\begin{aligned}\frac{\partial F(x)_2}{\partial x} &= (1-2\times 1)\left[1\times F(\alpha_2-\alpha_1) - c_1 - (1-1)c_2\right] \\ &= -F(\alpha_2-\alpha_1) + c_1 < 0\end{aligned} \tag{B.41}$$

This can never hold. **Unstable equilibrium.**

$$\begin{aligned}\frac{\partial F(y)_2}{\partial y} &= (1-2\times 1)\left[1\times p - 1\times(\beta s + I) - c_3\right] \\ &= -p + \beta s + I + c_3 < 0 \\ &\Leftrightarrow \beta s + I + c_3 < p\end{aligned} \tag{B.42}$$

This must hold.

$$\begin{aligned}\frac{\partial F\left(z\right)_2}{\partial z} &= \left(1-2\times 1\right)\left[1\times\left(\beta s+I\right)-I+\left(1\times\alpha_1+\left(1-1\right)\alpha_2\right)F\right] \\ &= -\beta s-\alpha_1 F<0\end{aligned} \tag{B.43}$$

This always holds.

B.3 Case 3

The nine inputs in the Jacobian matrix:

$$\frac{\partial F\big(x\big)_3}{\partial x} = \big(1-2x\big)\big[zF\big(\alpha_2-\alpha_1\big)-c_1+q\big] \tag{B.44}$$

$$\frac{\partial F\big(x\big)_3}{\partial y} = 0 \tag{B.45}$$

$$\frac{\partial F\big(x\big)_3}{\partial z} = x\big(1-x\big)F\big(\alpha_2-\alpha_1\big) \tag{B.46}$$

$$\frac{\partial F\big(y\big)_3}{\partial x} = 0 \tag{B.47}$$

$$\frac{\partial F\big(y\big)_3}{\partial y} = \big(1-2y\big)\big[-z\big(\beta s+I\big)-c_3\big] \tag{B.48}$$

$$\frac{\partial F\big(y\big)_3}{\partial z} = -y\big(1-y\big)\big(\beta s+I\big) \tag{B.49}$$

$$\frac{\partial F\big(z\big)_3}{\partial x} = z\big(1-z\big)\big(\alpha_1-\alpha_2\big)F \tag{B.50}$$

$$\frac{\partial F\big(z\big)_3}{\partial y} = z\big(1-z\big)\big(\beta s+I\big) \tag{B.51}$$

$$\frac{\partial F\big(z\big)_3}{\partial z} = \big(1-2z\big)\big[y\big(\beta s+I\big)-I+\big(x\alpha_1+\big(1-x\big)\alpha_2\big)F\big] \tag{B.52}$$

$\mathbf{E_4(0,0,1)}$

$$\begin{aligned}\frac{\partial F\left(x\right)_3}{\partial x} &= \left(1-2\times 0\right)\left[1\left(\alpha_2-\alpha_1\right)-c_1+q\right] \\ &= F\left(\alpha_2-\alpha_1\right)-c_1+q<0 \\ &\Leftrightarrow q<F\left(\alpha_1-\alpha_2\right)+c_1\end{aligned} \tag{B.53}$$

This must hold.

$$\begin{aligned}\frac{\partial F\left(y\right)_3}{\partial y} &= \left(1-2\times 0\right)\left[-1\times\left(\beta s+I\right)-c_3\right] \\ &= -\beta s-I-c_3<0\end{aligned} \tag{B.54}$$

This always holds.

$$\begin{aligned}\frac{\partial F(z)_3}{\partial z} &= (1-2\times 1)\left[0\times(\beta s+I)-I+(0\times\alpha_1+(1-0)\,\alpha_2)\,F\right]\\ &= I-\alpha_2 F<0\\ &\Leftrightarrow I<\alpha_2 F\end{aligned} \tag{B.55}$$

This must hold. **Not realistic.**

$\mathbf{E_6}(\mathbf{1},\mathbf{0},\mathbf{1})$

$$\begin{aligned}\frac{\partial F(x)_3}{\partial x} &= (1-2\times 1)\left[1\,(\alpha_2-\alpha_1)-c_1+q\right]\\ &= -F\,(\alpha_2-\alpha_1)+c_1-q<0\\ &\Leftrightarrow F\,(\alpha_1-\ \alpha_2)+c_1<q\end{aligned} \tag{B.56}$$

This must hold.

$$\begin{aligned}\frac{\partial F(y)_3}{\partial y} &= (1-2\times 0)\left[-1\times(\beta s+I)-c_3\right]\\ &= -\beta s-I-c_3<0\end{aligned} \tag{B.57}$$

This always holds.

$$\begin{aligned}\frac{\partial F(z)_3}{\partial z} &= (1-2\times 1)\left[0\times(\beta s+I)-I+(1\times\alpha_1+(1-1)\,\alpha_2)\,F\right]\\ &= I-\alpha_1 F<0\\ &\Leftrightarrow I<\alpha_1 F\end{aligned} \tag{B.58}$$

This must hold. **Not realistic.**

$\mathbf{E_7}(\mathbf{0},\mathbf{1},\mathbf{1})$

$$\begin{aligned}\frac{\partial F(x)_3}{\partial x} &= (1-2\times 0)\left[1\,(\alpha_2-\alpha_1)-c_1+q\right]\\ &= F\,(\alpha_2-\alpha_1)-c_1+q<0\\ &\Leftrightarrow q<F\,(\alpha_1-\alpha_2)+c_1\end{aligned} \tag{B.59}$$

This must hold.

$$\begin{aligned}\frac{\partial F(y)_3}{\partial y} &= (1-2\times 1)\left[-1\times(\beta s+I)-c_3\right]\\ &= \beta s+I+c_3<0\end{aligned} \tag{B.60}$$

This can never hold. **Unstable equilibrium.**

$$\begin{aligned}\frac{\partial F\left(z\right)_3}{\partial z} &= \left(1-2\times 1\right)\left[1\times\left(\beta s+I\right)-I+\left(0\times\alpha_1+\left(1-0\right)\alpha_2\right)F\right]\\ &= -\beta s-\alpha_2 F<0\end{aligned} \tag{B.61}$$

This always holds.

$\mathbf{E_8(1,1,1)}$

$$\begin{aligned}\frac{\partial F\left(x\right)_3}{\partial x} &= \left(1-2\times 1\right)\left[1\left(\alpha_2-\alpha_1\right)-c_1+q\right]\\ &= -F\left(\alpha_2-\alpha_1\right)+c_1-q<0\\ &\Leftrightarrow F\left(\alpha_1-\alpha_2\right)+c_1<q\end{aligned} \tag{B.62}$$

This must hold.

$$\begin{aligned}\frac{\partial F\left(y\right)_3}{\partial y} &= \left(1-2\times 1\right)\left[-1\times\left(\beta s+I\right)-c_3\right]\\ &= \beta s+I+c_3<0\end{aligned} \tag{B.63}$$

This can never hold. **Unstable equilibrium.**

$$\begin{aligned}\frac{\partial F\left(z\right)_3}{\partial z} &= \left(1-2\times 1\right)\left[1\times\left(\beta s+I\right)-I+\left(1\times\alpha_1+\left(1-1\right)\alpha_2\right)F\right]\\ &= -\beta s-\alpha_1 F<0\end{aligned} \tag{B.64}$$

This always holds.

B.4 Case 4

The nine inputs in the Jacobian matrix:

$$\frac{\partial F\big(x\big)_4}{\partial x} = (1-2x)\big[zF\big(\alpha_2-\alpha_1\big)-c_1-\big(1-y\big)c_2+q\big] \tag{B.65}$$

$$\frac{\partial F\big(x\big)_4}{\partial y} = x\big(1-x\big)c_2 \tag{B.66}$$

$$\frac{\partial F\big(x\big)_4}{\partial z} = x\big(1-x\big)F\big(\alpha_2-\alpha_1\big) \tag{B.67}$$

$$\frac{\partial F\big(y\big)_4}{\partial x} = y\big(1-y\big)p \tag{B.68}$$

$$\frac{\partial F\big(y\big)_4}{\partial y} = \big(1-2y\big)\big[xp-z\big(\beta s+I\big)-c_3\big] \tag{B.69}$$

$$\frac{\partial F\big(y\big)_4}{\partial z} = -y\big(1-y\big)\big(\beta s+I\big) \tag{B.70}$$

$$\frac{\partial F(z)_4}{\partial x} = z(1-z)(\alpha_1 - \alpha_2)F \tag{B.71}$$

$$\frac{\partial F(z)_4}{\partial y} = z(1-z)(\beta s + I) \tag{B.72}$$

$$\frac{\partial F(z)_4}{\partial z} = (1-2z)\left[y(\beta s + I) - I + (x\alpha_1 + (1-x)\alpha_2)F\right] \tag{B.73}$$

$\mathbf{E_4(0,0,1)}$

$$\begin{aligned}\frac{\partial F(x)_4}{\partial x} &= (1-2\times 0)\left[1(\alpha_2-\alpha_1) - c_1 - (1-0)c_2 + q\right]\\ &= F(\alpha_2-\alpha_1) - c_1 - c_2 + q < 0\\ &\Leftrightarrow q < F(\alpha_1-\alpha_2) + c_1 + c_2\end{aligned} \tag{B.74}$$

This must hold.

$$\begin{aligned}\frac{\partial F(y)_4}{\partial y} &= (1-2\times 0)\left[0\times p - 1\times(\beta s + I) - c_3\right]\\ &= -\beta s - I - c_3 < 0\end{aligned} \tag{B.75}$$

This always holds.

$$\begin{aligned}\frac{\partial F(z)_4}{\partial z} &= (1-2\times 1)\left[0\times(\beta s + I) - I + (0\times\alpha_1 + (1-0)\alpha_2)F\right]\\ &= I - \alpha_2 F < 0\\ &\Leftrightarrow I < \alpha_2 F\end{aligned} \tag{B.76}$$

This must hold. **Not realistic.**

$\mathbf{E_6(1,0,1)}$

$$\begin{aligned}\frac{\partial F(x)_4}{\partial x} &= (1-2\times 1)\left[1(\alpha_2-\alpha_1) - c_1 - (1-0)c_2 + q\right]\\ &= -F(\alpha_2-\alpha_1) + c_1 + c_2 - q < 0\\ &\Leftrightarrow F(\alpha_1-\alpha_2) + c_1 + c_2 < q\end{aligned} \tag{B.77}$$

This must hold.

$$\begin{aligned}\frac{\partial F(y)_4}{\partial y} &= (1-2\times 0)\left[1\times p - 1\times(\beta s + I) - c_3\right]\\ &= p - \beta s - I - c_3 < 0\\ &\Leftrightarrow p < \beta s + I + c_3\end{aligned} \tag{B.78}$$

This must hold.

$$\begin{aligned}\frac{\partial F(z)_4}{\partial z} &= (1-2\times 1)\left[0\times(\beta s+I)-I+(1\times\alpha_1+(1-1)\alpha_2)F\right]\\ &= I-\alpha_1 F<0\\ &\Leftrightarrow I<\alpha_1 F\end{aligned} \tag{B.79}$$

This must hold. **Not realistic.**

$\mathbf{E_7(0,1,1)}$

$$\begin{aligned}\frac{\partial F(x)_4}{\partial x} &= (1-2\times 0)\left[1(\alpha_2-\alpha_1)-c_1-(1-1)c_2+q\right]\\ &= F(\alpha_2-\alpha_1)-c_1+q<0\\ &\Leftrightarrow q<F(\alpha_1-\alpha_2)+c_1\end{aligned} \tag{B.80}$$

This must hold.

$$\begin{aligned}\frac{\partial F(y)_4}{\partial y} &= (1-2\times 1)\left[0\times p-1\times(\beta s+I)-c_3\right]\\ &= \beta s+I+c_3<0\end{aligned} \tag{B.81}$$

This can never hold. **Unstable equilibrium.**

$$\begin{aligned}\frac{\partial F(z)_4}{\partial z} &= (1-2\times 1)\left[1\times(\beta s+I)-I+(0\times\alpha_1+(1-0)\alpha_2)F\right]\\ &= -\beta s-\alpha_2 F<0\end{aligned} \tag{B.82}$$

This always holds.

$\mathbf{E_8(1,1,1)}$

$$\begin{aligned}\frac{\partial F(x)_4}{\partial x} &= (1-2\times 1)\left[1(\alpha_2-\alpha_1)-c_1-(1-1)c_2+q\right]\\ &= -F(\alpha_2-\alpha_1)+c_1-q<0\\ &\Leftrightarrow F(\alpha_1-\alpha_2)+c_1<q\end{aligned} \tag{B.83}$$

This must hold.

$$\begin{aligned}\frac{\partial F(y)_4}{\partial y} &= (1-2\times 1)\left[1\times p-1\times(\beta s+I)-c_3\right]\\ &= -p+\beta s+I+c_3<0\\ &\Leftrightarrow \beta s+I+c_3<p\end{aligned} \tag{B.84}$$

This must hold.

$$\begin{aligned}\frac{\partial F\left(z\right)_4}{\partial z} &= \left(1-2\times 1\right)\left[1\times\left(\beta s+I\right)-I+\left(1\times\alpha_1+\left(1-1\right)\alpha_2\right)F\right] \\ &= -\beta s-\alpha_1 F<0\end{aligned} \tag{B.85}$$

This always holds.

Appendix C

Appendix: Code - Sensitivity Analyses

All code below is inspired by code kindly shared by Tian Zhao, visiting PhD at CSEI[1].

Replicator dynamics equations

```
function dy= scenario1_innovation(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario2_innovation(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.4*(1-y(1)))*0.75);
end


function dy= scenario3_innovation(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-1.5*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(1.5*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario4_innovation(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.7-0.7*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.7);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario1_alpha1_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.1*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.6*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario1_alpha1_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.5*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(1*y(1)+0.5*(1-y(1)))*1);
end
```

[1]Copenhagen School of Energy Infrastructure

```
function dy= scenario1_beta_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-1.75*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(1.75*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end




function dy= scenario1_beta_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2.25*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2.25*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario1_p_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(3*y(1)-2*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario1_p_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(5*y(1)-2*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario1_q_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+3);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario1_q_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+5);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario2_alpha1_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.15*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.6*y(1)+0.4*(1-y(1)))*0.75);
end


function dy= scenario2_alpha1_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.45*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(1*y(1)+0.4*(1-y(1)))*0.75);
end


function dy= scenario2_beta_down_25(t,y)
```

```
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-1.75*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(1.75*y(2)-1+(0.8*y(1)+0.4*(1-y(1)))*0.75);
end


function dy= scenario2_beta_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2.25*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2.25*y(2)-1+(0.8*y(1)+0.4*(1-y(1)))*0.75);
end


function dy= scenario2_p_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(3*y(1)-2*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.4*(1-y(1)))*0.75);
end


function dy= scenario2_p_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(5*y(1)-2*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.4*(1-y(1)))*0.75);
end


function dy= scenario2_q_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+3);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.4*(1-y(1)))*0.75);
end


function dy= scenario2_q_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+5);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.4*(1-y(1)))*0.75);
end


function dy= scenario3_alpha1_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.1*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-1.5*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(1.5*y(2)-1+(0.6*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario3_alpha1_up_25(t,y)
dy=zeros(3,1);
```

```
dy(1,1)=y(1)*(1-y(1))*(-0.5*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-1.5*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(1.5*y(2)-1+(1*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario3_beta_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-1.375*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(1.375*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario3_beta_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-1.625*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(1.625*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario3_p_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(3*y(1)-1.5*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(1.5*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario3_p_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(5*y(1)-1.5*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(1.5*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario3_q_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+3);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-1.5*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(1.5*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario3_q_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.5-0.5*(1-y(2))+5);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-1.5*y(3)-0.5);
dy(3,1)=y(3)*(1-y(3))*(1.5*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario4_alpha1_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.1*y(3)-0.7-0.7*(1-y(2))+4);
```

```
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.7);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.6*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario4_alpha1_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.5*y(3)-0.7-0.7*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.7);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(1*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario4_beta_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.7-0.7*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-1.75*y(3)-0.7);
dy(3,1)=y(3)*(1-y(3))*(1.75*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario4_beta_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.7-0.7*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2.25*y(3)-0.7);
dy(3,1)=y(3)*(1-y(3))*(2.25*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario4_p_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.7-0.7*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(3*y(1)-2*y(3)-0.7);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario4_p_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.7-0.7*(1-y(2))+4);
dy(2,1)=y(2)*(1-y(2))*(5*y(1)-2*y(3)-0.7);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario4_q_down_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.7-0.7*(1-y(2))+3);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.7);
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end


function dy= scenario4_q_up_25(t,y)
dy=zeros(3,1);
dy(1,1)=y(1)*(1-y(1))*(-0.3*y(3)-0.7-0.7*(1-y(2))+5);
dy(2,1)=y(2)*(1-y(2))*(4*y(1)-2*y(3)-0.7);
```

```
dy(3,1)=y(3)*(1-y(3))*(2*y(2)-1+(0.8*y(1)+0.5*(1-y(1)))*1);
end
```

Evolutionary process towards the equilibrium in the four scenarios (figure 5.1)

```
subplot(2,2,1)
for i=0.2:0.2:0.8
for j=0.2:0.2:0.8
for m=0.2:0.2:0.8
tspan = [0;500];
[T,y] = ode45('scenario1_innovation',tspan,[i j m]);
figure(1)
y1=y(:,1);
y2=y(:,2);
y3=y(:,3);
plot3(y1,y2,y3);
hold on
grid on
xlabel('x','Fontsize',20)
ylabel('y','Fontsize',20)
zlabel('z','Fontsize',20)
title('Scenario 1', 'FontSize', 20)
axis([0 1 0 1 0 1])
ax.FontSize=20;
hold on
end
end
end

subplot(2,2,2)
for i=0.2:0.2:0.8
for j=0.2:0.2:0.8
for m=0.2:0.2:0.8
tspan = [0;500];
[T,y] = ode45('scenario2_innovation',tspan,[i j m]);
figure(1)
y1=y(:,1);
y2=y(:,2);
y3=y(:,3);
plot3(y1,y2,y3);
hold on
grid on
xlabel('x','Fontsize',20)
ylabel('y','Fontsize',20)
zlabel('z','Fontsize',20)
title('Scenario 2', 'FontSize', 20)
axis([0 1 0 1 0 1])
ax.FontSize=20;
hold on
end
end
end

subplot(2,2,3)
for i=0.2:0.2:0.8
for j=0.2:0.2:0.8
```

```
for m=0.2:0.2:0.8
tspan = [0;500];
[T,y] = ode45('scenario3_innovation',tspan,[i j m]);
figure(1)
y1=y(:,1);
y2=y(:,2);
y3=y(:,3);
plot3(y1,y2,y3);
hold on
grid on
xlabel('x','Fontsize',20)
ylabel('y','Fontsize',20)
zlabel('z','Fontsize',20)
title('Scenario 3', 'FontSize', 20)
axis([0 1 0 1 0 1])
ax.FontSize=20;
hold on
end
end
end

subplot(2,2,4)
for i=0.2:0.2:0.8
for j=0.2:0.2:0.8
for m=0.2:0.2:0.8
tspan = [0;500];
[T,y] = ode45('scenario4_innovation',tspan,[i j m]);
figure(1)
y1=y(:,1);
y2=y(:,2);
y3=y(:,3);
plot3(y1,y2,y3);
hold on
grid on
xlabel('x','Fontsize',20)
ylabel('y','Fontsize',20)
zlabel('z','Fontsize',20)
title('Scenario 4', 'FontSize', 20)
axis([0 1 0 1 0 1])
ax.FontSize=20;
hold on
end
end
end
```

Sensitivity analysis of α_1 (figure 5.2)

```
figure(5)
subplot(4,3,1);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario1_alpha1_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
```

```
hold on;
[t3,y3]=ode45('scenario1_alpha1_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario1_alpha1_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_alpha1_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(a)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast','FontSize',12);

subplot(4,3,2);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario1_alpha1_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_alpha1_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario1_alpha1_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_alpha1_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(b)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast','FontSize',12);

subplot(4,3,3);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario1_alpha1_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
```

```
hold on;
[t3,y3]=ode45('scenario1_alpha1_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario1_alpha1_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_alpha1_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(c)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast','FontSize',12);

subplot(4,3,4);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario2_alpha1_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_alpha1_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario2_alpha1_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_alpha1_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(d)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast','FontSize',12);

subplot(4,3,5);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario2_alpha1_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
```

```
hold on;
[t3,y3]=ode45('scenario2_alpha1_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario2_alpha1_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_alpha1_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(e)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast','FontSize',12);

subplot(4,3,6);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario2_alpha1_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_alpha1_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario2_alpha1_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_alpha1_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(f)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast','FontSize',12);

subplot(4,3,7);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario3_alpha1_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
```

```
[t3,y3]=ode45('scenario3_alpha1_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario3_alpha1_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_alpha1_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(g)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast','FontSize',12);

subplot(4,3,8);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario3_alpha1_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_alpha1_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario3_alpha1_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_alpha1_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(h)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast','FontSize',12);

subplot(4,3,9);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario3_alpha1_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
```

```
[t3,y3]=ode45('scenario3_alpha1_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario3_alpha1_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_alpha1_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(i)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast','FontSize',12);

subplot(4,3,10);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario4_alpha1_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_alpha1_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario4_alpha1_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_alpha1_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(j)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast','FontSize',12);

subplot(4,3,11);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario4_alpha1_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
```

```
[t3,y3]=ode45('scenario4_alpha1_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario4_alpha1_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_alpha1_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(k)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast','FontSize',12);

subplot(4,3,12);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario4_alpha1_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_alpha1_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario4_alpha1_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_alpha1_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(l)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast','FontSize',12);
```

Sensitivity analysis of β (figure 5.3)

```
figure(5)
subplot(4,3,1);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario1_beta_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
```

```
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_beta_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario1_beta_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_beta_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(a)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,2);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario1_beta_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_beta_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario1_beta_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_beta_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(b)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,3);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario1_beta_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
```

```
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_beta_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario1_beta_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_beta_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(c)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,4);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario2_beta_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_beta_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario2_beta_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_beta_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(d)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,5);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario2_beta_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
```

```
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_beta_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario2_beta_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_beta_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(e)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,6);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario2_beta_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_beta_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario2_beta_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_beta_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(f)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,7);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario3_beta_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
```

```
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_beta_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario3_beta_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_beta_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(g)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,8);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario3_beta_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_beta_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario3_beta_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_beta_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(h)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,9);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario3_beta_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
```

```
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_beta_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario3_beta_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_beta_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(i)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,10);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario4_beta_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_beta_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario4_beta_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_beta_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(j)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,11);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario4_beta_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
```

```
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_beta_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario4_beta_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_beta_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(k)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,12);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario4_beta_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_beta_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario4_beta_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_beta_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(l)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);
```

Sensitivity analysis of *p* (figure 5.4)

```
figure(5)
subplot(4,3,1);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario1_p_down_25',tspan,y0);
```

```
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_p_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario1_p_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_p_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(a)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,2);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario1_p_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_p_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario1_p_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_p_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(b)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,3);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario1_p_down_25',tspan,y0);
```

```
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_p_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario1_p_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_p_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(c)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,4);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario2_p_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_p_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario2_p_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_p_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(d)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,5);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario2_p_down_25',tspan,y0);
```

```
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_p_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario2_p_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_p_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(e)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,6);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario2_p_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_p_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario2_p_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_p_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(f)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,7);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario3_p_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
```

```
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_p_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario3_p_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_p_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(g)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,8);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario3_p_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_p_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario3_p_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_p_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(h)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,9);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario3_p_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
```

```
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_p_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario3_p_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_p_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(i)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,10);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario4_p_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_p_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario4_p_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_p_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(j)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,11);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario4_p_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
```

```
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_p_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario4_p_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_p_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(k)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,12);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario4_p_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_p_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario4_p_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_p_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(l)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);
```

Sensitivity analysis of *q* (figure 5.5)

```
figure(5)
subplot(4,3,1);
tspan=[0,10];
```

```
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario1_q_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_q_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario1_q_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_q_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(a)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,2);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario1_q_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_q_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario1_q_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_q_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(b)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,3);
tspan=[0,10];
```

```
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario1_q_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_q_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario1_q_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_q_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(c)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,4);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario2_q_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_q_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario2_q_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_q_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(d)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,5);
tspan=[0,10];
```

```
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario2_q_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_q_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario2_q_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_q_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(e)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,6);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario2_q_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_q_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario2_q_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_q_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(f)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,7);
tspan=[0,10];
y0=[0.8 0.8 0.8];
```

```
[t1,y1]=ode45('scenario3_q_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_q_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario3_q_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_q_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(g)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,8);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario3_q_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_q_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario3_q_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_q_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(h)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,9);
tspan=[0,10];
y0=[0.8 0.8 0.8];
```

```
[t1,y1]=ode45('scenario3_q_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_q_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario3_q_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_q_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(i)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,10);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario4_q_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_q_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario4_q_down_25',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,1),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_q_up_25',tspan,y0);
plot(t3,y3(:,1),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (x)', 'FontSize', 13);
title('(j)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,11);
tspan=[0,10];
y0=[0.8 0.8 0.8];
```

```
[t1,y1]=ode45('scenario4_q_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_q_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario4_q_down_25',tspan,y0);
plot(t1,y1(:,2),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_q_up_25',tspan,y0);
plot(t3,y3(:,2),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (y)', 'FontSize', 13);
title('(k)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);

subplot(4,3,12);
tspan=[0,10];
y0=[0.8 0.8 0.8];
[t1,y1]=ode45('scenario4_q_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_q_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
y0=[0.2 0.2 0.2];
[t1,y1]=ode45('scenario4_q_down_25',tspan,y0);
plot(t1,y1(:,3),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,3),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_q_up_25',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability (z)', 'FontSize', 13);
title('(l)', 'FontSize', 14)
legend('-25%','initial value','+25%','location','southeast', 'FontSize', 12);
```

Sensitivity analysis of x (figure 5.6)

```
figure(5)
```

```
subplot(4,3,1);
tspan=[0,10];
y0=[0.2 0.5 0.5];
[t1,y1]=ode45('scenario1_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(a)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,2);
tspan=[0,10];
y0=[0.5 0.5 0.5];
[t1,y1]=ode45('scenario1_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(b)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,3);
tspan=[0,10];
y0=[0.8 0.5 0.5];
[t1,y1]=ode45('scenario1_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(c)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);
```

```
subplot(4,3,4);
tspan=[0,10];
y0=[0.2 0.5 0.5];
[t1,y1]=ode45('scenario2_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(d)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,5);
tspan=[0,10];
y0=[0.5 0.5 0.5];
[t1,y1]=ode45('scenario2_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(e)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,6);
tspan=[0,10];
y0=[0.8 0.5 0.5];
[t1,y1]=ode45('scenario2_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(f)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);
```

```
subplot(4,3,7);
tspan=[0,10];
y0=[0.2 0.5 0.5];
[t1,y1]=ode45('scenario3_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(g)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,8);
tspan=[0,10];
y0=[0.5 0.5 0.5];
[t1,y1]=ode45('scenario3_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(h)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,9);
tspan=[0,10];
y0=[0.8 0.5 0.5];
[t1,y1]=ode45('scenario3_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(i)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);
```

```
subplot(4,3,10);
tspan=[0,10];
y0=[0.2 0.5 0.5];
[t1,y1]=ode45('scenario4_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(j)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,11);
tspan=[0,10];
y0=[0.5 0.5 0.5];
[t1,y1]=ode45('scenario4_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(k)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,12);
tspan=[0,10];
y0=[0.8 0.5 0.5];
[t1,y1]=ode45('scenario4_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(l)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);
```

Sensitivity analysis of *γ* (figure 5.7)

```
figure(5)
subplot(4,3,1);
tspan=[0,10];
y0=[0.5 0.2 0.5];
[t1,y1]=ode45('scenario1_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(a)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,2);
tspan=[0,10];
y0=[0.5 0.5 0.5];
[t1,y1]=ode45('scenario1_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(b)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,3);
tspan=[0,10];
y0=[0.5 0.8 0.5];
[t1,y1]=ode45('scenario1_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
```

```
title('(c)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,4);
tspan=[0,10];
y0=[0.5 0.2 0.5];
[t1,y1]=ode45('scenario2_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(d)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,5);
tspan=[0,10];
y0=[0.5 0.5 0.5];
[t1,y1]=ode45('scenario2_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(e)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,6);
tspan=[0,10];
y0=[0.5 0.8 0.5];
[t1,y1]=ode45('scenario2_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
```

```
title('(f)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,7);
tspan=[0,10];
y0=[0.5 0.2 0.5];
[t1,y1]=ode45('scenario3_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(g)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,8);
tspan=[0,10];
y0=[0.5 0.5 0.5];
[t1,y1]=ode45('scenario3_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(h)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,9);
tspan=[0,10];
y0=[0.5 0.8 0.5];
[t1,y1]=ode45('scenario3_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
```

```
title('(i)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,10);
tspan=[0,10];
y0=[0.5 0.2 0.5];
[t1,y1]=ode45('scenario4_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(j)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,11);
tspan=[0,10];
y0=[0.5 0.5 0.5];
[t1,y1]=ode45('scenario4_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(k)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,12);
tspan=[0,10];
y0=[0.5 0.8 0.5];
[t1,y1]=ode45('scenario4_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
```

```
title('(l)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);
```

Sensitivity analysis of *z* (figure 5.8)

```
figure(5)
subplot(4,3,1);
tspan=[0,10];
y0=[0.5 0.5 0.2];
[t1,y1]=ode45('scenario1_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(a)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,2);
tspan=[0,10];
y0=[0.5 0.5 0.5];
[t1,y1]=ode45('scenario1_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(b)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,3);
tspan=[0,10];
y0=[0.5 0.5 0.8];
[t1,y1]=ode45('scenario1_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario1_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario1_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
```

```
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(c)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,4);
tspan=[0,10];
y0=[0.5 0.5 0.2];
[t1,y1]=ode45('scenario2_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(d)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,5);
tspan=[0,10];
y0=[0.5 0.5 0.5];
[t1,y1]=ode45('scenario2_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(e)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,6);
tspan=[0,10];
y0=[0.5 0.5 0.8];
[t1,y1]=ode45('scenario2_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario2_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario2_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
```

```
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(f)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,7);
tspan=[0,10];
y0=[0.5 0.5 0.2];
[t1,y1]=ode45('scenario3_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(g)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,8);
tspan=[0,10];
y0=[0.5 0.5 0.5];
[t1,y1]=ode45('scenario3_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(h)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,9);
tspan=[0,10];
y0=[0.5 0.5 0.8];
[t1,y1]=ode45('scenario3_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario3_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario3_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
```

```
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(i)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,10);
tspan=[0,10];
y0=[0.5 0.5 0.2];
[t1,y1]=ode45('scenario4_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(j)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,11);
tspan=[0,10];
y0=[0.5 0.5 0.5];
[t1,y1]=ode45('scenario4_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(k)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);

subplot(4,3,12);
tspan=[0,10];
y0=[0.5 0.5 0.8];
[t1,y1]=ode45('scenario4_innovation',tspan,y0);
plot(t1,y1(:,1),'-m','LineWidth',2);
hold on;
[t2,y2]=ode45('scenario4_innovation',tspan,y0);
plot(t2,y2(:,2),'--r','LineWidth',2);
hold on;
[t3,y3]=ode45('scenario4_innovation',tspan,y0);
plot(t3,y3(:,3),'-.b','LineWidth',2);
hold on;
```

```
grid on;
axis([0 10 0 1])
xlabel('Time (t)', 'FontSize', 13);
ylabel('Probability', 'FontSize', 13);
title('(l)', 'FontSize', 14)
legend('x','y','z','location','southeast', 'FontSize', 12);
```