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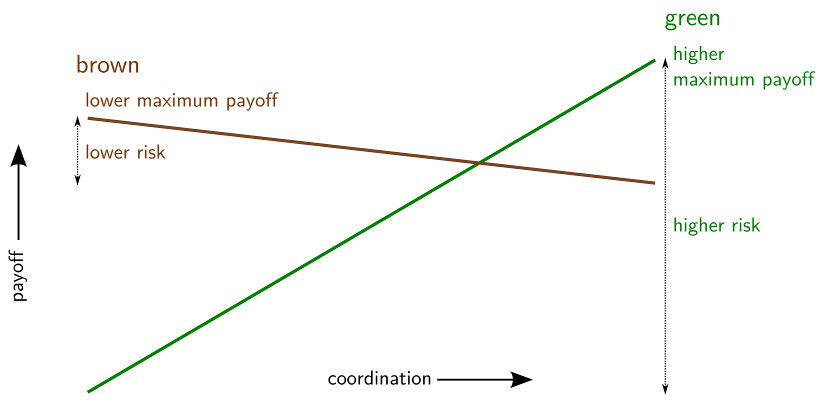
Green investment and coordination failure: An investors' perspective

Jahel Mielke[α β *] · **Gesine A. Steudle**[α]



[α] Global Climate Forum, Berlin
[β] University of Potsdam
*E-mail: jahel.mielke@globalclimateforum.org

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Abstract The goal to keep global warming well below 2°C entails the opportunity to globally drive green and sustainable growth. To achieve this climate target, private investors have to shift capital from brown to green infrastructures and technologies. In this paper, we present a game-theoretic perspective on the transition from brown to green growth. Instead of having one equilibrium, like in a prisoners dilemma, the authors perceive investment for mitigation and adaptation as a coordination problem of selecting among multiple equilibria. To illustrate this, we model a non-cooperative coordination game, related to the stag hunt, with a brown equilibrium with lower payoffs that can be achieved single-handedly and a green equilibrium with higher payoffs that requires coordination. As multiple experiments show, actors often fail to coordinate on a payoff dominant equilibrium in such games due to uncertainty. Thus, we discuss how uncertainty could be reduced along two options: one that concerns a change in the payoff structure of the game and another that concerns subjective probabilities. The latter option draws on social norms, narratives and signals for green investment as a means to coordinate expectations towards green growth.

Keywords stag hunt · coordination failure · green investment · strategic uncertainty · risk dominance

1 Introduction

The commitment to keep temperature rise well below 2°C, and desirably below 1.5°C, creates major investment needs in the coming decades (OECD (2015), Global Commission on the Economy and Climate (2014), World Economic Forum (2013)). Climate change mitigation and adaptation thus require a shift of capital from brown to green infrastructures and technologies (Qureshi (2016)). Currently, the investment gap to adjust the European energy sector in line with the climate targets amounts to €100 bn annually until 2030 (Berndt et al (2016)). The question why there is an underinvestment in green infrastructure and technologies is often addressed by bringing forward the argument of market failure. Zenghelis (2011) claims that, due to spillover effects from technological progress and due to ignorance towards positive externalities, the private sector tends to underinvest in mitigation technologies, and hence needs to be incentivized. Minsky and Whalen (1996) relate the neglect of infrastructure investments in the US and the increased financial instability since the 1980s to what they call "money-manager capitalism", meaning that financial markets, instead of servicing the real economy, are dominated by investors that rely on short-term-financing and that focus on a maximization of returns via dividends and shareholder value. Mazzucato and Penna (2015) unite the concepts of market and coordination failure by highlighting that in situations "when agents are unable to coordinate their expectations and preferences throughout the business cycle, due to information asymmetries and high screening costs" a Pareto-inferior equilibrium is obtained leading to a lack of investment.

Since game theory has a long tradition of analyzing coordination in the presence of multiple equilibria, we use a game-theoretic approach to discuss capital allocation to green and

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brown infrastructures and technologies. In a simple model of a non-cooperative coordination game, related to the stag hunt with two stable Nash equilibria, the role of expectations and trust among investors when making decisions for brown or green investment is being examined. The coordination problems, which arise in such games, can lead to coordination failure, i.e. the selection of a Pareto-inferior equilibrium.

To explain coordination on certain equilibria, the game-theoretic literature provides a broad variety of equilibrium selection principles and coordination mechanisms. For static games, deductive equilibrium selection principles[1], defined by Haruvy and Stahl (2004) as being "based on reasoning and coordination on focal points", can be applied. In this case, players are assumed to have "beliefs consistent with some equilibrium". Two well-known examples, payoff dominance (Harsanyi and Selten (1988); Schelling (1960)) and risk dominance (Harsanyi and Selten (1988), Harsanyi (1995), will be discussed in detail in this paper.

By drawing on experiments and by using a model of brown and green investment, we show the limitations of these principles and discuss further mechanisms that could lead to coordination.

This paper is organized as follows: Section 2 explains the problem of equilibrium selection in coordination games, using the examples of the stag hunt and the equilibrium selection principles of risk dominance and payoff dominance. Furthermore, experiments that have dealt with these principles are described briefly. Section 3 develops a coordination game of investors in an economy with green and brown investment strategies resembling a stag hunt. By calculating the risk dominant and the payoff dominant equilibrium, we discuss the effects of uncertainty on agents' equilibrium selection. In section 4, we look into coordination mechanisms that can influence expectations, leading to an overview of possible signals (Storper and Salais (1997), Zenghelis (2011), Skyrms (1987)) for coordination on green investment. Section 5 concludes with macro-economic considerations.

2 Equilibrium selection in coordination games

Whenever more than one strict pure-strategy Nash equilibrium exists in a game, refinements cannot predict a unique solution. Thus, the problem of equilibrium selection arises (Harsanyi and Selten (1988)). Under such conditions, players face a coordination problem, which can lead to coordination failure, i.e. "the failure to obtain a Pareto-optimal equilibrium" (Straub (1995), p. 340). In this section, the authors will use a well-known coordination game with two pure-strategy Nash equilibria, the stag hunt, as an illustrative example and discuss two equilibrium selection principles as developed by Harsanyi and Selten (1988) – payoff dominance and risk dominance. Section 2.3 provides an overview of influential experiments which tested these selection principles.

2.1 The stag hunt

When the French philosopher Jean-Jaques Rousseau laid the foundations for the well-known two-by-two player game called stag hunt, he illustrated a social dilemma that contrasts collective and individual rationality: "That is how (primitive) men may have gradually acquired a crude idea of mutual commitments and the advantage of fulfilling them, but only insofar as their present and obvious interest required it, because they knew nothing of foresight, and far from concerning themselves with the distant future, they did not even think of the next day. If a group of them set out to take a deer, they were fully aware that

[1] Inductive selection principles, in contrast, emphasize learning (see e.g. Van Huyck et al (1997); Golman and Page (2009); Kandori et al (1993); Binmore and Samuelson (1999); Knez and Camerer (2000); Fudenberg and Levine (1998)) and evolutionary dynamics (see e.g. Pacheco et al (2009); Young (1993); Crawford (1991)) in order to predict an equilibrium in iterated games.

		hunter 2	
		hunt stag together	hunt hare alone
hunter 1	hunt stag together	3 / 3	0 / 2
	hunt hare alone	2 / 0	2 / 2

Table 1 A 2x2 stag hunt game.

they would all have to remain faithfully at their posts in order to succeed; but if a hare happened to pass near one of them, there can be no doubt that he pursued it without a qualm, and that once he had caught his prey, he cared little whether or not he had made his companions miss theirs." (Rousseau (1974), p. 175)

Hence, in the game-theoretic derivation of this paragraph, two pure Nash equilibria exist: Cooperation on hunting the stag leads to the efficient equilibrium, delivering higher payoffs[2] for all players, whereas uncertainty about the other players action leads to a Pareto-inferior outcome and thus an inefficient equilibrium where both players hunt a hare. Table 1 illustrates a classical stag hunt game with a payoff of 3 for both players hunting the stag and a payoff of 2 each when both individually hunt a hare. While in a prisoners dilemma, the mutually beneficial solution does not emerge because of an individual incentive not to cooperate, in a stag hunt, achieving the mutually beneficial solution depends on trust, making it a conflict between mutual benefit and personal risk (see Skyrms (2004)).

Although used much less than the prisoners dilemma, the stag hunt has been studied in different variations and forms. It is e.g. used to describe collective action problems (Medina (2007), Pacheco et al (2009), Harrison and Hirshleifer (1989)) or social structures (Skyrms (2004)). Evolutionary game theorists have extended it to more players and iterated it (Skyrms (2007); Binmore and Samuelson (1999); Moreira et al (2012); Young (1993)). Others applied it to macro-economic ideas (Bryant (1994); Cooper and John (1988)). Since the stag hunt exhibits more than one Nash equilibrium, game theorists seek the help of selection criteria in order to obtain a stable solution. There is an established literature on deductive equilibrium selection principles, like payoff dominance, as well as an emerging literature on inductive ones, such as social learning in iterated games (Golman and Page (2009); Skyrms (2008)). The next section will provide a closer look at payoff dominance and risk dominance that can later be used in our investment game.

2.2 Payoff dominance and risk dominance

In their 'General Theory of Equilibrium Selection', Harsanyi and Selten (1988) developed the criteria of payoff and risk dominance for non-cooperative 2x2 games with two pure-strategy equilibria in order to find answers to the coordination problem described above. Payoff dominance can be described as follows: When r and s are equilibrium points of the fixed standard form n-players game $G = (\Phi, H)$ with the pure strategy combination set $\Phi = \times_{i \in \{1 \ldots, n\}} \Phi_i$ and a payoff function $H : \Phi \to \mathbb{R}^n$, r payoff-dominates s if $H_i(r) > H_i(s)$ for every $i \in \{1 \ldots, n\}$. Thus, the Nash equilibrium with the largest payoff is considered being the payoff dominant one.

The risk dominant equilibrium is based on pairwise comparison of equilibria and can be determined via their Nash products. The Nash product reflects each players opportunity cost of unilaterally deviating from the equilibrium. For the example given in Table 1, the Nash product of the stag equilibrium is 2, and the one of the hare equilibrium 4. Since the latter is larger, the hare equilibrium is the risk dominant one, while the stag equilibrium is payoff dominant. In their derivation of the Nash-product, Harsanyi and

[2] The question of the relationship of payoffs and utility and the derived implications for risk needs further research that is beyond the scope of this paper.

Selten (1988) consider the thresholds for the subjective probabilities a player has to assign to the behaviour of the others in order to decide which strategy to choose. In the example of Table 1 this means: If hunter 1 assumes hunter 2 to hunt the stag with a probability of more than $p_S^{(1)} = 2/3$ he will choose to hunt the stag as well, while he has to assume the other to hunt the hare with a probability larger than $p_H^{(1)} = 1/3$ in order to go hare hunting himself. In the following, we will call these probabilities risk factors of the player for the respective equilibrium. To determine risk dominance, it is equivalent to compare the products of these probability thresholds (i.e. $p_H^{(1)} p_H^{(2)}$ and $p_S^{(1)} p_S^{(2)}$ in our case) or the Nash products (see Harsanyi and Selten (1988)). The one with the larger Nash product has the smaller risk factor and is risk dominant. For a symmetric game as in our example, the risk factors are the same for both players, and thus it is sufficient to only compare $p_S^{(i)}$ and $p_H^{(i)}$.

For a game like the stag hunt that allows to Pareto-rank equilibria, Harsanyi and Selten claim that collective rationality makes "risk-dominance considerations irrelevant"[3] since "rational individuals will cooperate in pursuing their common interests if the conditions permit them to do so" (Harsanyi and Selten (1988), p. 356). This implies that if there is a single Pareto-efficient equilibrium point, there is no uncertainty about the outcome of the game and, hence, actors will coordinate on the equilibrium with the highest payoff for all. Schelling (1960) also supports this perception with his concept of tacit bargaining which states that if there is a clearly Pareto-superior solution for all, people will coordinate on this focal point even when communication is impossible. A rational player would always want to maximize his expected utility and, consequently, hunters would coordinate on hunting the stag (payoff dominant equilibrium) instead of the hare. Following this logic, risk dominance would only become relevant when the beliefs, integrated via subjective probabilities[4] over the other players strategies, imply an uncertain outcome of the game, e.g. in a battle of the sexes game. The view presented above has been challenged in various experiments, which will be described in the next section.

2.3 Experiments

A broad variety of laboratory experiments with coordination games tests Harsanyi and Selten's concepts of payoff dominance and risk dominance. Most of them conclude that players often do not coordinate on the Pareto-optimal equilibrium (see e.g. Camerer (2003)). Van Huyck et al (1990) showed that strategic uncertainty leads to coordination failure, because people choose security over efficiency[5]. Also, their experiment suggests that the larger the group of players, the stronger the tendency of coordination failure. In another experiment, an opinion game with a payoff-dominant equilibrium and a secure equilibrium, van Huyck et al observed that "repeated interaction produced simple dynamics that converged to the inefficient equilibrium" (Van Huyck et al (1991), 885f). Schmidt et al (2003) found that a change in the payoff structure of the game exerts less influence on equilibrium selection than a change in the risk structure. Battalio et al (2001) altered optimization premiums in order to investigate convergence towards the inefficient risk-dominant equilibrium. Cooper et al (1990, 1992) reject the notion of Pareto-dominance and showed that dominated strategies can have an influence on equilibrium selection. Aumann (1990) demonstrated that in the absence of enforceable agreements, like contracts, pre-play communication ("cheap talk") on equilibrium selection does not influence players and thus not lead to the payoff-dominant equilibrium. Straub, who performed repeated two-person

[3] Harsanyi (1995) later revised his assumption that players always choose the payoff dominant equilibrium over the risk dominant equilibrium and henceforth used only risk dominance as an equilibrium selection criterion for non-cooperative games.

[4] Sudgen (2000) goes a step further, trying to introduce normative expectations into conventional games by including higher order strategies

[5] Risk dominance was not explicitly tested in Van Huyck et al (1990).

coordination games, concludes that "coordination failures are a replicable empirical regularity and that risk dominance is crucial in explaining coordination failures" (**?** p. 352). The experiments mentioned above show that agents have difficulties to coordinate on the Pareto-optimal equilibrium and display the limitations of deductive equilibrium selection principles.

3 A stag hunt of brown and green investment

In this section, we develop a basic model that aims at illustrating how a stag-hunt-like structure can arise in a game where investors are faced with choosing different technologies. The idea is not to provide quantitative evaluations for a specific economy, but to identify a game structure that can later help to discuss the influence of social norms, narratives and signals on coordination. For that, let us assume that investors can choose to invest in one of two available technologies – a green and a brown one. Both investments are connected with a respective payoff P which depends on the player's own investment and on the behaviour of the others. The more players invest in a technology, the higher their payoffs become. This represents increased acceptance and maturity for a technology, making the investment more profitable as e.g. unit costs decrease (economies of scale)[6]. Thus, the investor's payoff entails two components: One relates to the investor's own engagement and consists of a return on investment proportional to the invested quantity (with factor r), as well as investment costs (factor c). The other is a return proportional to the total investments in the respective technology.

We define our investment game as follows: There are n players (investors) with two possible strategies– S_G and S_B – to choose from. S_G means to invest a certain amount I in the green technology, while S_B means investments of the same amount I in the brown technology. For the investment of player i, the sum of her green investments G_i and brown investments B_i, thus either holds $G_i = I$ and $B_i = 0$ (strategy S_G), or $G_i = 0$ and $B_i = I$ (strategy S_B). The payoff P_i of player i is then given by

$$P_i = (r_g - c_g) \cdot G_i + \frac{\gamma}{n} \sum_{j=1}^{n} G_j = g \cdot G_i + \frac{\gamma}{n} \sum_{j=1}^{n} G_j \tag{1}$$

if S_G is chosen, and

$$P_i = (r_b - c_b) \cdot B_i + \frac{\beta}{n} \sum_{j=1}^{n} B_j = b \cdot B_i + \frac{\beta}{n} \sum_{j=1}^{n} B_j \tag{2}$$

if player i chooses S_B. Here, γ, β, g, and b are the constant parameters that account for the respective returns. We assume that the established technology is mature and widespread[7], and that returns on investments do not depended very strongly on what other investors do, whereas for the new technology total investments are crucial for gaining acceptance and diffusion. In our example, we consider brown capital as the established one and green capital to be the new technology. Therefore we choose $\gamma > \beta$ and $b > g$.

To give an example of the resulting game structure, for $n = 3$ players and $I = 1$, $\gamma = 7$, $\beta = 2$, $g = 4$, and $b = 8$, the payoffs for player i playing S_G or S_B are given in Table 2. This game has two pure-strategy Nash equilibria, a green equilibrium (all players choose to play green) and a "brown" one (all players choose brown). The green equilibrium is strictly Pareto-superior and results in the highest possible payoff for all players.

[6] An IPCC special report links the cost decrease, e.g. for wind energy, to learning and higher production or capacity via experience curves (Edenhofer et al (2012)).

[7] Binmore (1994) defines the less risky equilibrium in a stag hunt as the "state of nature"– comparable to our brown strategy– while an agreement for a social contract is defined as riskier but beneficial– relating to our green strategy.

		other players		
		S_G, S_G	S_G, S_B S_B, S_G	S_B, S_B
player i	S_G	11.0	8.7	6.3
	S_b	8.7	9.3	10.0

Table 2 Payoffs of player i in the green and brown investment game.

We assume that the players maximise their expected utility, which is based on the payoffs of the game and on beliefs, i.e. player i develops expectations about the behaviour of the other players by assigning probabilities to their possible actions. In our simple model, she does not differentiate and expects both other players to behave similarly. Let p_G be player i's subjective probability of the other players choosing green, and p_B her probability for the others choosing brown. Player i's expected payoff for playing strategy S_j is then given by

$$E\left[P(S_j)\right] = p_G^2 \cdot P(S_j|S_G S_G) + p_B^2 \cdot P(S_j|S_B S_B) + p_G p_B \cdot (P(S_j|S_G S_B) + P(S_j|S_B S_G)) \quad (3)$$

with $P(S_j|S_k S_l)$ being the payoff for player i playing S_j, given that the other players choose S_k and S_l, respectively.

Payoff dominance as a selection criterion in this case would mean that players automatically select the Pareto-superior equilibrium ($p_G = 1$, $p_B = 0$). If we reject this notion, we consider strategic uncertainty to influence equilibrium selection. To evaluate the risk dominant equilibrium, we calculate risk factors for both Nash equilibria as described in section 2.2. We assume that players consider the other players as equal, i.e. they assume equal probabilities p_G, $p_B = 1 - p_G$ to play green or brown for all the other players. For the payoff table given in Table 2, player i chooses to play green if he assumes that the others play green with a probability $p_G > p_G^* = 0.61$, and consistently, chooses to play brown if he expects the others to play brown with a probability of $p_B > p_B^* = 0.39$. That means that in this example the Pareto-inferior Nash equilibrium is risk dominant, and in case that a player considers the others to choose playing brown with a probability of more than 0.39, he chooses the strategy associated with the Pareto-inferior equilibrium[8].

To use a more realistic setting, we increase the number of players to 101. The structure of the game stays unchanged. In Figure 1, payoffs of a player investing in green (blue line) or brown (red line), versus the number of others playing green is shown. In this game, two Nash equilibria exist, one if all players choose green and another if all players choose brown. The green Nash equilibrium is Pareto-superior with a risk factor of $p_G^* = 0.67$, the brown equilibrium results in a lower payoff for all players and has a risk factor of $p_B^* = 0.33$.

γ and $-\beta$ determine the slopes of the curves, and g and b shift them vertically. Our assumptions $\gamma > \beta$ and $b > g$ result in a steeper curve and a lower minimum for the case of the player playing green. To invest in brown can be considered less risky as the associated risk factor is smaller than 50%.

The intersection of the two curves can be seen as a *tipping point*. On the left side of the intersection, the share of investment in the green technology is too small to make it more profitable than brown investment, while on the right side of it, the total share of green investment is that large that green investment becomes more profitable for the individual player.

[8] In Cooper and John (1988), spillovers lead to inefficient equilibria and, thus, to coordination failure.

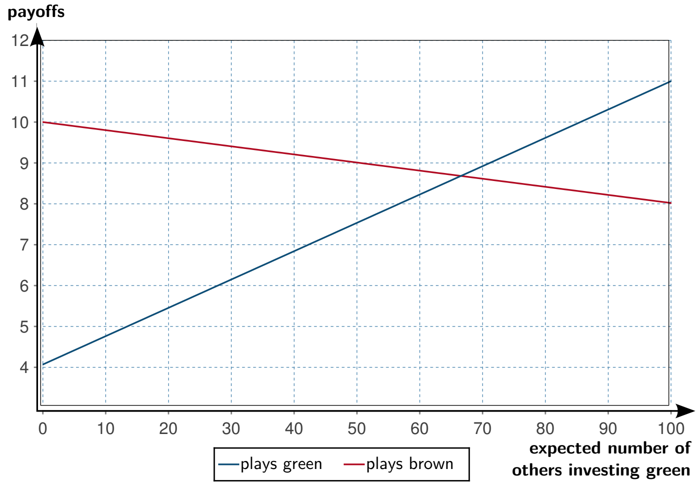

Fig. 1 Expected payoffs for one player in a 101-player investment game.

4 Discussion

We have found that our simple game-theoretic model of investment decisions[9] between two technologies reveals a stag-hunt like structure with a risk dominant and a payoff dominant equilibrium. If we assume that actors are uncertain about the outcome of the game, there is a need to discuss what can influence their expectations. Thus, in section 4.1, we will discuss coordination mechanisms for equilibrium selection of a brown or a green equilibrium. Section 4.2 will relate these ideas to green investment.

4.1 Coordination Mechanisms

As illustrated before, experiments with stag-hunt like games indicate that although it would be collectively rational, people are not likely to choose payoff dominance as an equilibrium selection strategy due to a lack of mutual trust in the behaviour of the others. Van Huyck et al. believe that rational decision makers in economies with multiple equilibria will be influenced by strategic uncertainty[10] "even in situations where objectives, feasible strategies, and institutions are completely specified and are common knowledge" (Van Huyck et al (1991): 885f). Schelling, even though adhering to the concept of focal points, acknowledged that "the principles relevant to successful play, the strategic principles, (and) the propositions of a normative theory, cannot be derived by purely theoretical means from a priori considerations" (Schelling (1960), p. 162). If more than payoffs are considered to

[9] With respect to investment, technical progress through learning by doing, i.e. increase by overall investment, exhibits the game theoretic structure of a prisoner's dilemma. This discussion is beyond the scope of this paper and thus shall be only sketched briefly: In economic growth models, technological progress is often assumed to be exogenous, and is e.g. modelled to be exponentially increasing over time (Moore's Law). However, there is empirical evidence that one of the main drivers of productivity growth is 'learning by doing', i.e. the productivity increases the faster the more output is produced, or proportionally to the capital stock. Usually, it is assumed that this productivity growth is the same for all producers, i.e. if induced by the expansion of the capital stock of one firm it benefits all the others as well. Barro and Sala-i-Martin (2004) showed that if every firm (owning a small capital stock compared to the overall capital stock) neglects the impact of its own investment on the productivity growth, investment is lower than in the optimal case. For that case, Barro and Sala-i-Martin suggest to internalize this external effect, e.g. through a subsidy for investments, financed by the revenues of a tax on consumption.

[10] Strategic uncertainty among rational actors has been described by many scholars, among them Keynes (1936) with the concept of the beauty contest.

have an influence on players' choices, other coordination mechanisms[11] such as social norms (Nyborg et al (2016), Binmore and Samuelson (1994), Skyrms (2008), Burke and Young (2011), Gintis (2010)), signals or narratives (Jaeger et al (2012), Wolf et al (2016), Morgan (2012)) could influence players' expectations.

In our simple model we assume that players choose their strategies evaluating expected payoffs. Expected payoffs are determined by payoffs and subjective probabilities (see equation (3)), and thus there are two entry points for such mechanisms:

1. A change in the game, i.e. the payoff function (equations (1) and (2)) This would e.g. correspond to subsidies for green investment as a coordination mechanism, which in the model would be represented by a larger g. Increasing g shifts the blue curve upwards (Figure 1) and thus reduces the risk factor for the green equilibrium[12].
2. A change of the players' expectations. The subjective probabilities assigned to the behaviour of the others are crucial for the investors' choice of strategy. There are many attempts to deduce these probabilities endogenously from the structure of the game alone (Binmore (1994), Harsanyi and Selten (1988), Sudgen (2000)). However, since our model is not a stand-alone tool to draw lessons from, we consider it useful for discussing how to influence subjective probabilities exogenously, because they are crucial for the question of at which side of the tipping point the players will allocate themselves.

Combinations of both options could be effective. For example, feed-in-tariffs for renewables or similar measures that support green investment, could reduce the risk factor of the green equilibrium by altering the payoff table (and thus the structure of the game). At the same time, they can influence players' subjective probabilities on the likelihood of other players to choose playing green due to a stronger belief in the transition and future profits from green investment. Beckert supports this argumentation by saying that it is only possible to resolve coordination problems, "if market actors are able to form stable expectations with regard to the actions of other market actors and future events relevant for their decisions, and if they consider the expected outcomes to be sufficiently in their material interest and normatively acceptable." (Beckert (2009), p. 247).

In the context of the transition towards green investment in our basic model, the question is how to make investors expect that the others will invest in green[13]. There are several approaches that consider influencing players' expectations exogeneously: Cachon and Camerer (1996) conclude that framing payoffs as gains or losses could alleviate coordination failure in repeated play. Corsetti et al (2003) discuss that liquidity support by the International Monetary Fund (IMF) can foster coordination in financial crises. Bryant (1994) emphasizes that out of a non-equilibrium situation of an economy, institutions or expectations could help actors to coordinate more efficiently than just prices. Most examples of such mechanisms take effect in repeated games where players can learn to coordinate themselves. The literature also gives insight on coordination mechanisms for firms: Lorenzen (2001) provides an example by distinguishing incentive coordination mechanisms, such as monitoring, and cognitive coordination mechanisms, such as reputational effects. Storper and Salais (1997) name growth opportunities and technological opportunities as two important coordination signals companies receive. To further investigate how to possibly change the players' subjective probabilities, more insight could be obtained by introducing repetitions into our one-shot model so that players can learn to coordinate.

4.2 Coordination on the green investment strategy

Our simple model relates to climate policy, considering green investment a contribution to mitigation. It is useful to discuss reasons why players might assume that green investments

[11] Cooper and John (1988) state that "if there was a mechanism for agents to coordinate their activities, they could achieve a better (cooperative) equilibrium."
[12] This was tested and confirmed by Schmidt et al (2003).
[13] Such a mechanism of expectation dynamics has already been investigated in Jaeger et al (2011).

of other players are unlikely. At the moment, the mitigation discourse is dominated by the argument of economic costs we have to shoulder today (i.e. accept a welfare reduction) in order to avoid future risks and losses due to consequences of global warming. This reasoning has been described as the tragedy of the commons (Hardin (1968)) or as a collective action dilemma (Carraro (2003)). Olson (1965) linked these ideas to the prisoner's dilemma. Thus, in a world with limited capacity to absorb additional CO_2 in the atmosphere, and that incentivizes actors to burn fossil fuels, we are trapped in a prisoner's dilemma with the only Nash equilibrium being that everyone makes use of the resources in an unsustainable way and chooses not to mitigate (defect)[14]. The metaphor of the prisoner's dilemma, thus, can have a negative impact on the expectation that a transition towards a 2°C scenario is likely to be achieved. If we assume that the players of our investment game live in an environment in which this narrative is prevalent in the public discourse, shaped by civil society, market actors and policy makers, their probabilities for expecting the others to invest in green might be low.

Let us assume that, on the contrary, the players of our investment game live in a society in which the public discourse on climate mitigation is dominated by the idea of a stag hunt, presuming that there is another possible Nash equilibrium which is characterised by the use of greener technologies that lead to less CO_2 at (at least) the same level of growth. This Nash equilibrium, categorized as a "green growth"[15] trajectory, would be considered a stable state of the economy. In such an environment, our players' probabilities for expecting the others to invest in green technologies would be higher than in the case where climate mitigation is associated with a prisoner's dilemma[16].

Coming back to the two options for coordination mechanisms, a framework of possible signals for green investment can be derived. The first option includes policy and market signals that change the parameters of the payoff functions, such as feed-in tariffs or a maturing market. The second option contains signals that relate to social norms, such as civil society pressure, or leadership, reputation and transparency (Ostrom (2009)) by market players. Mielke (2017) describes such a framework of policy, market and civil society actions that build on the model of investment decisions presented in this paper.

5 Conclusion

Climate change mitigation and the necessary investments to decarbonize the economy can be understood as a social dilemma. Inaction, often characterized as individually reasonable behaviour, leads to a deficient equilibrium. Although the prisoner's dilemma is a more commonly used metaphor in the discourse on climate change, we find that the stag hunt provides a more suitable framework for discussing green investment strategies. If expectations of actors can be reframed towards green growth, e.g. through a credible climate policy, narratives or investment incentives, coordination on a Pareto-superior equilibrium could be reached. However, Straub, who described coordination failure as a "conflict between individual rationality (risk dominance) and collective rationality and the inability of agents to select actions as a group" (Straub (1995), p. 4), argues that risk dominance will always prevail in a single-shot game without communication. Thus, the study of dynamic stag hunts (Skyrms (1987)), e.g. in the context of well-known growth models (Steudle et al

[14] Kruitwagen et al (2016), Nordhaus (2015), Wood (2010), and Heugues (2013) apply the prisoner's dilemma to climate change.

[15] By green growth, we mean sustainable growth that combines ecological, economic and social aspects. For an economic assessment of green growth, see Wolf et al (2016).

[16] Ostrom, in an attempt to update the theory of collective action, supports this positive perspective in saying that "while many instances of free riding are observed in the array of empirical research, a surprisingly large number of individuals facing collective action problems do cooperate" (Ostrom (2009), p. 10). The chances of cooperation increase, e.g. if actors have reliable information on costs and benefits of actions, operate with a long-term time horizon, value a reputation for being a trustworthy reciprocator and experience leadership for joint problem solving.

(2017)), as well as the study of coordination mechanisms for investors (Mielke (2017)), provide an interesting basis for further research. Since green technologies are still associated with higher risks, there is an incentive for institutional investors to choose brown technologies. However, our model exhibits a tipping point, where players' assumptions about the probability with which the others invest in the green technology exceeds the necessary threshold, above which a player considers her green expected payoff higher than the brown one. Therefore, we conclude that trust and expectations are crucial in achieving the green equilibrium.

The brown and green investment game presented in section 3 entails a micro-economic perspective through the selection of Nash equilibria among investors. Stag-hunt structures can be used as models that help to explain macro-economic states such as Keynesian coordination failures (Romer (1996)) and equilibrium selection in economies (Goeree and Holt (2005); Bryant (1994); Cooper and John (1988)), too. Cooper and John (1988) investigate the connection of strategic complementarities and spillovers with multiple equilibria as well as multiplier effects and find that spillovers lead to inefficient equilibria. They describe the situation where an economy gets stuck "at an inefficient equilibrium with a low level of 'economic activity', even though a better equilibrium exists", as coordination failure. Bryant (1983) modelled an economy with agents producing at many different sites. Although they have rational expectations, they only reach an inferior equilibrium. In a later effort, Bryant (1994) developed a two-step production game that develops from a prisoner's dilemma into a stag hunt.

This relates to our ideas of green growth: The current state of the European economy could e.g. be described as a brown equilibrium. Emissions are still too high, while at the same time the EU is experiencing low growth rates and low investment levels, making it difficult to mobilize capital for decarbonization[17]. Some authors have developed an idea of a possibly better growth path, associated with the green growth narrative (Jaeger et al (2015)), leading to a Pareto-optimal green growth equilibrium. If we consider this option as a possible alternative, these two macro states of the economy can also be percieved as a stag hunt: We are stuck in the risk-dominant brown equilibrium while there is another payoff-dominant green equilibrium out there. As large-scale green investments would be necessary for achieving that green-growth equilibrium, this 'macro stag hunt' is clearly related to the considerations sketched in our investors' model. How these connections look like precisely is beyond the scope of this work but clearly invites further research.

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[17] ECB-president Mario Draghi described this situation as having "(. . .) large parts of the euro area in what we call a 'bad equilibrium', namely an equilibrium where you may have self-fulfilling expectations that feed upon themselves and generate very adverse scenarios" (Draghi (2012)).

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