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RESEARCH

Technology Diffusion and Climate Action: A Leader–Follower Model

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Abstract

Can a small technology-developing country increase technology diffusion to developing countries in climate action? We argue that when a country takes into account all direct and indirect benefits from pushing forward the transnational diffusion of national green technology, a free transfer may give the country a net benefit. This result is driven by the idea that technology transfer partnerships enable the countries to tailor technology development to best fit the special circumstances of receiving countries. Such decentralised cooperation can pave the way for scalable technology diffusion. The focus is on one country's renewable energy technology development and how this can affect climate action in major developing countries such as China and India. We propose a leader–follower model between the technology-developing country and the developing country that allows complex payoffs and focuses on a situation in which one country makes a cooperative move to solve the inherent collective action problem. This effective shared learning platform has an upscaling potential, and international organisations, such as the European External Action Service, could further facilitate technology diffusion to developing countries.

Keywords Leader–follower model · Technology diffusion · Developing countries · Climate action · Denmark · China · European External Action Service

1 Introduction

A couple of years ago, one of the authors was on a summer holiday with his family in Miami Beach, Florida. Here, he spotted a huge oceangoing Maersk containership making a 90° turn within a surprisingly short distance. It was a breath-taking and

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thought-provoking experience. After studying the topic, he found that such a swift manoeuvre is possible because of the ingenious mechanism called a “trim tab”, which is a small rudder on a large rudder: “And there’s a tiny thing at the edge of the rudder called a trim tab. It’s a miniature rudder. Just moving the little trim tab builds a low pressure that pulls the rudder around. Takes almost no effort at all” [1].

In this way, a small rudder moves the large rudder, which again moves the entire ship. This metaphor of the simple “trim tab effect” can be applied to climate action as well; a small green technology-developing country such as Denmark could be the trim tab, and a large developing country and CO_2 emitter such as China could be the ship. Such an upscaling potential to other developing countries is massive, implying more sustainable economic development as well.

At the moment, the Danish Energy Agency has taken unilateral action to cooperate with seven developing countries, namely, China, South Africa, Mexico, Indonesia, Vietnam, Ukraine, and Turkey. Assisting these countries in their transition from polluting greenhouse gas emissions and at the same time maintaining stable economic growth should be a catalyst for other countries to join in and, together, achieve the target level in the Paris Agreement (COP21). In this way, the present cooperation allows a small technology leader such as Denmark to unilaterally influence two billion energy consumers, responsible for one-third of the world’s total CO_2 emissions [2]. Even a small technology leader can in this way make a major difference in the green transition in developing countries. This leads us to the following research question: Can a small technology-developing country increase technology diffusion to developing countries in climate action?

Political internalisation of negative impacts can be incorporated [3, 4]. Actually, the EU and the UN already made the first attempt to incorporate those negative impacts in the Kyoto Protocol from 1997 by the use of a global burden-sharing agreement for the reduction of greenhouse gases [5]. To meet the Paris target of 1.5 °C, global emissions need to be cut by 7.6% every year for the next decade [6]. China’s target under the Paris Agreement is that its CO_2 emissions should peak no later than 2030, including a target for the share of non-fossil fuels in the primary energy supply to be at least 20% in 2030. Even under the most optimistic assumptions, where the share of non-fossil fuels in primary energy supply grows to 30%, the development in China’s total CO_2 emissions is incomparable with the emissions reduction target from the UN of 1.5 °C [6].

This in spite of the fact that China has achieved stronger environmental governance in recent years, especially under Xi Jinping [7]. Moreover, China has initiated a number of environmental policy experiments such as low-carbon cities [8]. Still, these until now inadequate attempts have led small countries such as Denmark to look for more efficient opportunities to affect the climate in a positive direction. To succeed in this, knowledge about the best technology in the field of energy must be shared to an even higher degree. As argued by Swatuk et al. [4], “Climate action is necessary, and necessarily must be better informed in order to achieve the broadest socio-ecological benefits possible”. Climate action in China—i.e. the world’s largest greenhouse gas emitter accounting for 29.4% of the world’s CO_2 emissions in 2017—will here have a relatively stronger impact

[9]. In comparison, Denmark accounts for less than 0.15% of global greenhouse gas emissions [9].

In 2017, 43.6% of Denmark's electricity came from wind power, and the expected share in 2020 is 50% (Dansk [10]. Thus, in 2014, the Danish Energy Agency (in collaboration with the Danish Ministry of Foreign Affairs) launched technology diffusion initiatives [11]. They say the following about these initiatives: "Since 2012, we have offered the full range of Denmark's experience, expertise, and innovation to countries undergoing their own energy transformations. Why? Because building a low-carbon economy requires global action and global collaboration" [12].

In the theoretical leader–follower model, the actors are countries. Therefore, the overall objective of a country is important when we evaluate its choice of policy to promote and support national technology development and diffusion. While export revenue and employment matter, a country may also pursue objectives such as maximising green technology diffusion because of environmental concerns or to be perceived as a responsible nation. There will, of course, be trade-offs in pursuing such objectives.

A country that initiates ambitious national climate action will face a trade-off between tailoring the necessary technological transition to fit its national circumstances and tailoring the technology to the specific circumstances in countries that will potentially adopt the technology. The initiating country will thereby increase its climate impact. For a small country such as Denmark, a partnership with a developing country such as China would provide the necessary scaling potential. A partnership could build a platform for shared learning that generates the best-fit technology, yielding significant benefits for both participating countries [13]. Second, scaling is important from a global perspective involving other major developing countries such as India and Brazil, which may be addressed by European public policies, too.

The Danish-Chinese climate partnership can be theorised as a prisoner's dilemma. As argued by Olson [14], actors in large groups need selective incentives or private benefits to solve collective action problems, for example, when trying to provide the public good of climate change mitigation [15, 16]. In order to analyse the conditions under which a partnership can be profitable for both parties, we set up a leader–follower model that allows complex payoffs and focuses on a situation in which one country makes a cooperative move.

The focus will be on renewable energy technology development by one country and how this can affect climate action in other countries. Given this setting, the possibility of a partnership initiative may solve the collective action problem, obtaining the largest possible diffusion to developing countries. It is key to identify the net benefit for both parties and the net global environmental benefits. The literature generally gives an indication of where and when states should intervene but does not give much specific advice on how this should be achieved optimally in real-life policy, such as climate partnerships [17–19]. Furthermore, promoting green technology is an immediate policy concern but both politically and administratively troublesome [20, 21].

In the following, we specifically examine whether a leader–follower model can be a realistic future model for compliance and technology diffusion to developing countries. First, Sect. 2 introduces technology diffusion. Next, Sect. 3 presents the case of a partnership initiative between Denmark and China. Then, Sect. 4 develops the leader–follower model. Finally, Sect. 5 concludes.

2 Technology Diffusion

Barrett [22] and Sandler [23] identify the climate problem as a voluntary provision to a global public good. Thus, all countries enjoy the global climate effort whether they contribute to it or not [24–26]. Already from its start, the institution for combatting global climate change had as its prime normative principle of "common but differentiated responsibility". Article 3 of the United Nations Framework Convention on Climate Change (UNFCCC) states that "…, the developed country parties should take the lead in combating climate change and the adverse effects thereof". While this initially was motivated by distributional and capacity motives, this was also interpreted, by the EU, as a necessity for a "motivational push" by a leader by example [27].

The EU sees itself as a leader in the climate issue and has repeatedly announced and acted upon its aim of being an international leader by example in climate action and assisting developing countries [28, 29]. For example, the EU and India have adopted a Joint Declaration on a clean energy and climate partnership [30]. Miguel Arias Cañete, European Commissioner for climate action and energy, has said: "As a major world player, India is a crucial partner for the EU on energy and climate matters. I look forward to deepening our already fruitful relationship with this new partnership. Together, the EU and India can boost energy security and fight climate change through a clean and sustainable energy system" (ibid.).

Senior EU politicians know there is room to improve the present state of EU external policy. Thus, the high representative for foreign and security policy, Josep Borrell, has argued that Europe should learn the "language of power" "…and take the lead on critical policy issues such as climate, cyber, and Africa" [31], 9). Thus, the European Council has recently renewed the EU's commitment to place climate action at the centre of external policy and "…highlights that the EU needs to urge third countries to intensify their efforts alongside the EU, and support them in their endeavours through all EU external policy instruments. The conclusions also stress the importance of stepping up outreach activities on climate action with partner countries…" [32].

The mechanisms through which positive responses can emerge are manifold. The responses can be triggered by setting a good example, by providing a motivational push [27], or by providing and signalling valuable information where a leader has superior information about relevant parameters [33, 34]. If a lack of knowledge on preferences or the relative value of avoiding climate change discourages national climate actions, a leader's action may then provide this knowledge [35].

The development of clean technologies is one way for unilateral climate action in one nation to produce direct effects in developing countries. The importance of technology development for achieving climate targets is recognised in IPCC [36]. However, there are many barriers to technology diffusion. Keller [37] uses a technology diffusion model, based on foreign direct investment data where the diffusion is tied to physical distance. It shows that diffusion is restricted to distance. The notion of socio-economic distance as an important factor restricting global diffusion as well as steering its direction through cultural, administrative, geographic, and economic distance has also been raised by Ghemawat [38]. Major barriers to broad diffusion and deployment of these green technologies are relatively high investment costs, uncertain demand, and uncertainty about learning effects [39].

In Greaker et al. [40], a discussion is presented about whether an industrialised country should develop a technology that is a "best fit" to its own situation or that fits a developing country. Zhang et al. [39] argue that a multi-scale learning process enables most cost reductions by combining learning by doing, regional learning, and cluster learning, that is, learning spillovers across technologies that rely on certain technologies, by maximising experience and knowledge accumulation.

Partnerships between green technology leaders and developing countries can thereby provide a shortcut to accelerate global diffusion. A shared learning partnership has several positive effects as it provides an ideal mechanism for accelerating technology diffusion between the two partners. This argument builds on theory and observation that technology knowledge diffusion is faster in a country with a shared common language and where inventors communicate more regularly and are geographically closer to each other, thus facilitating an alignment of interests [41, 42].

3 Technology Diffusion from Denmark to China

In the following, we show that the present energy mix in China is yet far from a low-carbon society as in many other developing countries. Figure 1 shows two possible paths that developing countries could follow in their pursuit of increased economic welfare: a high emission path, which is represented by the path consistent with the development of, for instance, the USA, and a low emission path as signified by Denmark. If China would copy the USA in the future, it would significantly keep on increasing its emissions.

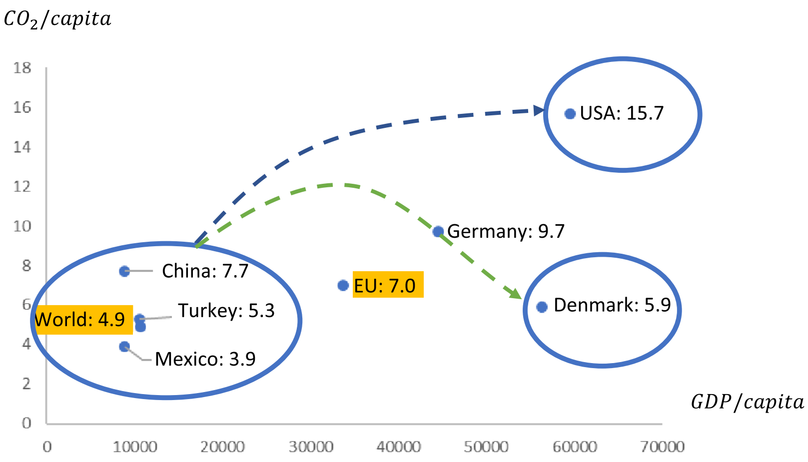
Recently, China has slowly moved to the North-East in the diagram, as indicated in Fig. 2.

Even though emissions are increasing, the speed of this increase is slowing down. And this is mainly due to an increase in energy efficiency and a smaller carbon intensity of energy/electricity production [45].

The total electricity production in China is fast-growing, and so is the amount of electricity produced by wind and solar panels, see Table 1.

Table 1 provides data on the share of wind and solar PV to the total electricity production. However, even though the share of coal in the energy mix has fallen (from 77% in 2007 to 67% in 2018), the total amount continues to rise (+0.9% in 2018) [46]. This leads analytics to conclude that China is not on track regarding its transition to a low-carbon society [47].

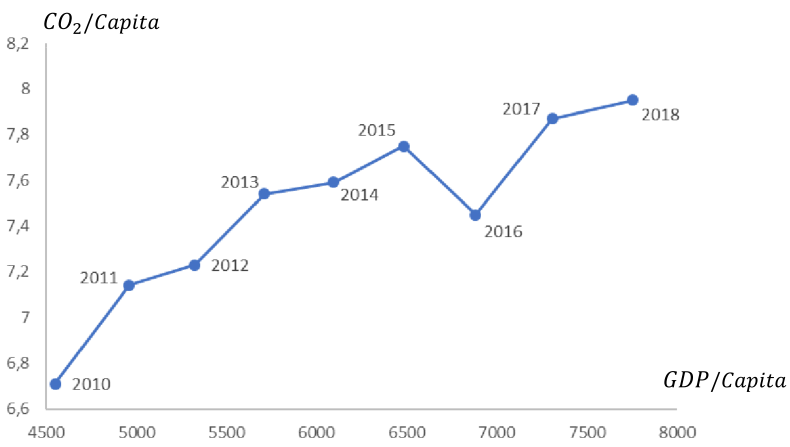
Technology diffusion means sharing: "…the Danish experiences on shaping an energy system that combines a green, low-carbon and reliable energy supply with economic growth". [48]. Most prominently, the Quality Wind project (QW) from 2015 was developed as a cooperation between the Danish Energy Agency and the



Source: The authors. Data from Trading Economics (2020).

Fig. 1 Development in selected countries CO_2/capita and GDP/capita (nominal), 2018. Source: The authors. Data from Trading Economics [43]

Danish wind turbine industry. The aim is to disseminate technology to developing countries such as China (Danish Energy Agency 2014). Denmark has a long experience in optimising wind turbine performance and energy efficiency [11]. The QW project builds exactly on this know-how and facilitates cooperation between Denmark and first and foremost China. The aim is: "…to increase awareness on how high standards for components and maintenance affects the performance of



Source: Trading Economics (2020) and Knoema (2020).

Fig. 2 Development in China's CO_2 per capita and GDP per capita (nominal). Source: Trading Economics [43] and Knoema [44]

Table 1 Development in electricity production and share of wind and solar PV for China (totals in GWh)

	Total	Change	Wind	Change	Solar PV	Change	Share to total
2014	5,678,945	4.3%	156,078	10.5%	29,195	89.0%	3.3%
2015	5,859,958	3.2%	185,766	19.0%	45,225	54.9%	3.9%
2016	6,217,907	6.1%	237,071	27.6%	75,256	66.4%	5.0%
2017	6,452,900	3.8%	304,600	28.5%	117,800	56.5%	6.5%
2018	6,994,000	8.4%	366,000	20.2%	177,500	50.7%	7.8%

BP [46]

turbines". Focus in QW is on efficient operation and maintenance (O&M), simply because Danish wind turbine producers cannot compete on price alone in China [2].

The early development of green technology in Denmark was accelerated after the first oil crisis in 1973. Before then, energy production relied primarily on oil imported from the Middle East. A strategy to become less dependent on politically unstable regions and achieve higher supply security was to subsidise renewable energy such as wind energy [49]. Here, operation and maintenance are important factors due to the heavy stress on wind turbines and the potential loss following the fatigue of components:

> A wind turbine on a good site in Denmark will, in a normal year, produce electricity for 6,500 hours which means that the turbine is producing 75% of the time. As modern turbines are constructed to be in operation for 20 years the turbine will be producing for approx. 130,000 hours in its lifetime. During the 20 years the main shaft will have rotated about 200 million times. To put it short, the stress on the construction is far more than what most other machines experience in their service life (Danish Energy Agency 2015c).

Consequently, the provision of service and components for entire wind farms from Denmark to China has caught much attention from the Chinese National Energy Agency which wants to gain access to this know-how through the QW [50]:

> Two of China's most innovative wind developers, Datang Renewables and SDIC, are participating in the Quality Wind project to investigate the potential for improving the performance of existing turbines in China. Their willingness to investigate how innovative technologies and best in class operation and maintenance can enhance performance even further and reduce cost of energy is crucial to the project. Datang Renewables and SDIC are currently exploring the opportunities for commercial cooperation with Danish suppliers of technology and O&M services. It is expected that cooperation will result in an increase of full load hours with an acceptable payback time to the Chinese investors. The Danish Energy Agency and China's National Energy Administration are facilitating the cooperation and will explore how the experiences of the Quality Wind project can be applied on a larger scale in China [2].

The Danish Energy Model entailed that wind power increased to 43.4% of the energy consumption in 2017. Lars Christian Lilleholt, the Danish Minister of

Energy, Utilities and Climate at the time, stated that by 2030, Denmark should have: "… at least 50% of its energy covered by renewable energy such as wind and solar power". This can also "…lead to more green jobs, especially in the wind industry" [51]. Such Danish knowledge about a specific technology in the field of energy can be spread and shared with other countries worldwide:

> Denmark is trying to stimulate and inspire low-carbon growth globally. Through the power of example, Denmark has demonstrated that energy consumption and carbon emissions can be radically improved in a short timeframe while maintaining a sound and resilient economy. An important part of the Danish effort to mitigate climate change will be through international cooperation [11].

As stated by the European External Action Service (EEAS), the EU faces many collective action problems such as security, refugee problems, and climate change. However, the EU is "…a global leader in environmental protection and the fight against climate change, promoting sustainable development through international cooperation, innovation, and clean energy" [28]. Concerning climate action, a shift in policy paradigm towards more partnership instruments is needed according to the EEAS:

> Through the Partnership Instrument (PI), introduced in the budget 2014–2020, the EU cooperates with partners around the world to advance the Union's strategic interests and tackle global challenges. The PI is to fund activities that carry forward EU agendas with partner countries, translating political commitments into concrete measures, in various areas of key interest to the EU. This funding is intended to support the external dimension of EU internal policies – in areas like competitiveness, research and innovation, as well as migration – and to help in addressing major global challenges such as energy security, climate change and environmental protection [52], 22).

4 The Leader–Follower Model

Based on this case, our aim in this section is to develop a leader–follower model of technology development that can help us understand the conditions for successful technology diffusion to developing countries. The model is based on the idea that partnerships are voluntary arrangements that should provide a clear and identifiable net benefit for both parties and that effective climate partnerships should also result in net global environmental benefits. The point of departure will be that one country, called the technology-developing country, will invest in new clean technology and that diffusion of the technology will provide sufficient benefits to warrant that investment.

4.1 Unilateral Action

Many papers use simple game-theoretic models to analyse the complex multinational interaction of the climate change issue. DeCanio and Framstad [53], for

Table 2 The static, two-country emission game

		Country 2	
		A_2	D_2
Country 1	A_1	$(b_1^2 - c_1, b_2^2 - c_2)$	$(b_2^1 - c_1, b_1^1)$
	D_1	$(b_1^1, b_2^1 - c_2)$	(0, 0)

The payoffs explained: $P_1(A_1, A_2) = b^2$ (benefit from both countries' abatement) − Ec_1 (expected costs of abatement for country 1)

example, address the relevance of 2×2 games. First, we set up a very simple game that identifies the underlying direct economic incentive structure that countries face. The starting point for the analysis is a two-player, one-period, two-strategy, simultaneous pollution problem for a uniformly mixed pollutant.

In this game, the payoffs for the two countries consist of individual costs and benefits from abatement and the benefits to each from the total number of countries that abate. Each county,$i = 1, 2, i$, has the choice between two actions: to adopt the clean technology (A_i), akin to cooperation, or continue using the dirty technology (D_i). There is no uncertainty about the payoffs. The abatement costs, that is, the net cost of adopting the clean technology, can be expressed as follows:

$$C_i(A_i) = c_i > 0, i = 1, 2$$

$$C_i(D_i) = 0, i = 1, 2$$

While the costs of abatement are solely borne by the abating country, since the pollutant is uniformly mixed, both countries benefit from emissions reduction by one country. Hence, only the total amount of abatement effort is relevant for the benefit. Let A^0, A^1, A^2 indicate that none, one, or both abate, respectively. The individual benefits from abatement are then assumed to be:

$$B_i(A^0) = 0, i = 1, 2$$

$$B_i(A^1) = b_i^1, i = 1, 2$$

$$B_i(A^2) = b_i^2 i = 1, 2$$

Assume that $b_i^2 \leq 2 \bullet b_i^1 i = 1, 2$, which implies that the benefit function is concave in abatement effort and that $b_i^2 > c_i$, while $b_i^1 < c_i$, such that the game is interesting at all. For these costs and benefits, a generic game-matrix in a one-period setting is specified in Table 2.

Depending on the payoff structure, various outcomes of this game can be predicted. Incentives for free riding for country i, identified as not abating given that the other country chooses to abate, will occur if: $b_i^2 - b_i^1 < c_i, i = 1, 2$. Likewise, for both countries abating, $b_i^2 - b_i^1 \geq c_i, i = 1, 2$. We occasionally write $\Delta b_i = b_i^2 - b_i^1$. The Nash equilibrium will consist of the countries choosing

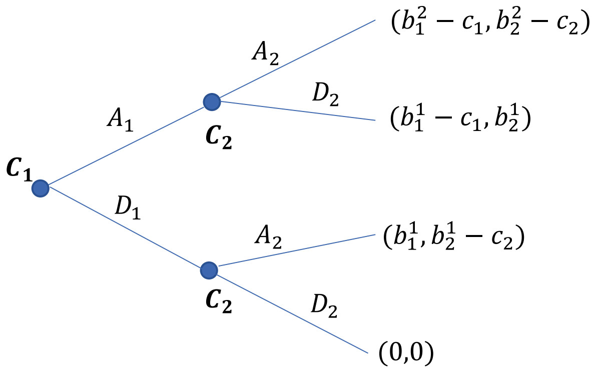


Fig. 3 The leader–follower game structure

(D_1, D_2), given that $\Delta b_i < c_i, i = 1, 2$. From a position where both abate, it is optimal for both to deviate and choose the free-riding strategy, such that the individual contribution is not optimal.

In this set-up, will a unilateral move, for instance, by committing to strict climate action, have the potential to change the outcome of this game?[1] A unilateral action is best interpreted as having a sequential move structure, and it will require to change the game into a sequential game. One technology-developing country (country 1 in Fig. 3) is the initiator and unilaterally moves first. This move is observed by the developing country (country 2), which then decides whether to abate or defect, see Fig. 3.

The condition that unilateral action of A_1 will not be met by A_2, but by defection from country 2, in the sense that D_2 is a best reply to A_1 is that $b_2^1 > b_2^2 - c_2 => c_2 > \Delta b_2$.

The condition $b_1^1 < c_1$ will imply that country 1 (given that the above condition is met) will not undertake unilateral action as D_1, given this condition is met, is a best reply to D_2. Since the conditions are the same as in the simultaneous game, no change occurs, and mutual defection will be optimal.[2]

4.2 Direct and Indirect Benefits, Technology Spillover, and Diffusion

In this section, we generalise the ideas of the preceding section. Focus is on renewable energy technology developed by country i. This country will bear the full costs of research and development (IC_i). Even though the research and development efforts make the renewable energy technology in question cheaper and more efficient, we assume that the technology still produces energy that is more costly than

1 In the Nash equilibrium, unilateral abatement is not rational since $b_1^1 < c_i$. However, collectively, it will be rational since $b_i^2 > c_i$.

2 In a continuous setting, Hoel [56] finds that unilateral action by one country will result in an increase in the emission of the other country. Several papers have identified situations where unilateral actions might reverse Hoel's result, see, e.g. Brandt [35] and Schwerhoff [57].

the dirty technology it will substitute. Investment might be worthwhile as it has the potential to generate a variety of benefits. We focus on support for clean technology development in country i ($+T$ indicates that this country will develop; $-T$ indicates that it will not). We further assume that if country i develops the technology, it automatically chooses A_i.

Several benefits occur when a country changes to the clean technology, A_i. It will be helpful to distinguish between national and global benefits from this action. There are direct (national) benefits, b_i^D, from using the clean technology, including less local air pollution, better access to energy, job creation, and export gains etc. Such benefits can differ from country to country and the direct economic, political, and psychological benefits accrue to the technology-producing country (are contained in initial investment costs and added as negative costs). Some of these effects are dependent on the level of diffusion of the technology to other countries.[3] There are global (indirect) benefits from choosing A_i, denoted b_i^{ID} due to the provision of the public good of less global pollution, which then provides benefits to all countries (which might not be identical from country to country).

Let k_j be the k units of the technology that country j will adopt, and let n be the number of countries adopting the technology.[4] The total adoption (diffusion) of the technology is:

$$T_i^{Total} = \sum_{j=1}^{n} k_j \cdot T_i = \sum_{j=1}^{n} T_j$$

The net benefit for country i if developing the technology and given the total diffusion of the technology T_i^{Total} is:

$$NB_i\left(T_i\right) = b_i^D(T_i) + b_i^{ID}\left(T_i^{Total}\right) - IC_i(T_i) - c_i(T_i)$$

If some other countries choose not to use the technology, we have defection (D_j) in which case $NB_j\left(D_j\right) = b_j^{ID}\left(T_{-j}^{Total}\right)$, such that this country can enjoy the indirect benefits from those countries that do adopt the technology (identified by T_{-j}^{Total}). On the other hand, if these other countries choose to adopt by using T_j units of the technology, the net benefit is given by:

$$NB_j\left(T_j\right) = b_j^D(T_j) + b_j^{ID}\left(T_{+j}^{Total}\right) - c_j(T_j)$$

For a given country j, the choice between T_j and D_j (given that m other countries have adopted the technology, and for a given optimal size k_j) can be shown in an inter-

[3] EU (2017) analyses direct benefits from being a first mover on technology development. Here, the technology spillovers impact the EU economy through two main channels. First, a negative impact through the reduction of the first-mover advantage. Second, a positive impact through stimulating world demand for EU products as the adoption of EU patents enables non-EU manufacturers to produce carbon-free technologies at low costs and hence adjust better to a low-carbon energy system.

[4] In the case of the BCP, we could set $n = 1$, but there might also be spillover effects to other countries due to achievements of the partnership.

action between the technology-developing country and the developing country as an extensive form game (game tree). See Fig. 4.

The figure is interpreted as follows: for country j, the decision whether to adopt the technology (choosing T_j) or not to adopt the technology (choosing D_j) depends on the relative net benefits this country receives from choosing one over the other strategy. Choosing T_j will be optimal if:

$$NB_j\left(T_j\right) \geq NB_j\left(D_j\right) => b_j^D(T_j) + b_j^{ID}\left(T_j^{Total}\right) - c_j(T_j) > b_j^{ID}\left(T_{-j}^{Total}\right) =>$$

$$b_j^D\left(T_j\right) + b_j^{ID}\left(T_j^{Total}\right) - b_j^{ID}\left(T_{-j}^{Total}\right) \geq c_j(T_j) =>$$

$$b_j^D\left(T_j\right) + \Delta b_j^{ID}\left(T_j^{Total}\right) \geq c_j\left(T_j\right)$$

This condition states that the total gain from adopting the technology should not be lower than the direct cost of adopting the technology.

Note that if country j is small, such that $\Delta b_j^{ID}\left(T_j^{Total}\right) \approx 0$, then the above condition reads $b_j^D\left(T_j\right) \geq c_j\left(T_j\right)$. For a large country, adopting the technology would already be optimal even for cases with a slightly negative value of $b_j^D\left(T_j\right) - c_j\left(T_j\right)$.

For the technology-developing country, the situation is more complex since its technology can be adopted by several countries and to varying degrees. Without developing, $T_i = 0$, the game remains in the initial prisoner's dilemma form, and an equilibrium of mutual defection can be expected. It should develop the technology, if $NB_i\left(T_i\right) \geq NB_i(0) = 0$, implying that:

$$b_i^D\left(T_i\right) + b_i^{ID}\left(T_j^{Total}\right) - IC_i\left(T_i\right) - c_i\left(T_i\right) \geq 0$$

Conditions for both the technology-developing country and countries potentially choosing the new technology are:

Country i: $b_i^D\left(T_i\right) + b_i^{ID}\left(T_j^{Total}\right) - IC_i\left(T_i\right) - c_i\left(T_i\right) \geq 0$

Country j: $b_j^D\left(T_j\right) + \Delta b_j^{ID}\left(T_j^{Total}\right) \geq c_j(T_j)$

The larger the national benefits $b_j^D(T_j)$ and the lower the costs of the technology, country j is more likely to adopt the technology. If country i carries on with technol-

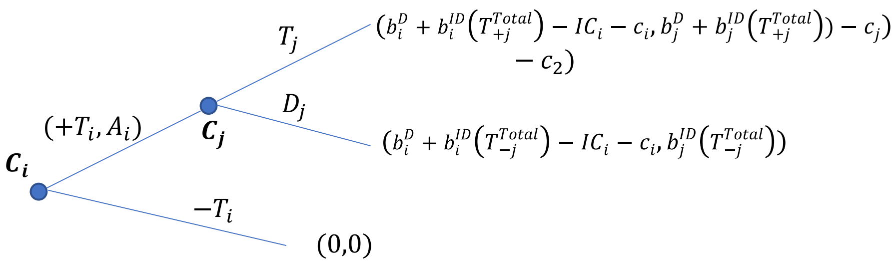


Fig. 4 Interaction and technology

ogy, technological and more broadly knowledge spillovers can potentially also create value in other countries. From these two conditions, we draw the conclusion that technology is adopted by followers if the added benefit of adopting is larger than the added costs of doing so. This is more likely, the larger the direct local environmental benefits or "co-benefits". Co-benefits from adopting CO_2-reducing technologies like cleaner electricity-producing technologies, such as wind power plants and solar PV installations, and electrical vehicles (EVs) will most like substitute more polluting technologies such as coal-powered plants and diesel buses and thereby improve the local air quality. Additionally, other local benefits are better energy supply, technology transfer, green jobs, etc. Finally, indirect environmental benefits could also occur. The technology-developing country will also experience indirect environmental benefits when the follower countries adopt the cleaner technology since CO_2 is a global pollutant.

4.3 Partnership Models

When a country develops a new technology, it is most likely based on local knowledge and on what will be the best fit technology version for the country. This means it is based on the desire to maximise that country's $b_i^D(T_i)$. However, the country that develops the technology faces a trade-off between maximising the probability that the technology will fit other countries' circumstances and the need to base the cost and the efficiency of the technology on local knowledge. Iyer et al. [54] find that even in the presence of aggressive climate action, the diffusion of technologies may be limited by several institutional, behavioural, and social factors. Furthermore, the technology and knowledge spillover is "uncontrolled",that is, it is not tailored to specific objectives. The question is then which type of mechanism can minimise this trade-off. A low-cost and effective way could be to engage in partnerships as addressed in the next section.

When will a renewable energy technology developed in one country be attractive to other countries? This depends on both the cost of the technology (acquiring and installing the technology) and on country-specific factors [54] such as how it fits into existing infrastructure (e.g. energy sector), geographic conditions, and natural flow resources, shallow waters etc. National plans for climate, renewable energy, and economic growth also matter. We model this by introducing a vector of best fit factors, γ_j, based on country j's specific circumstances given the relevant economic, social, political, and technological/infrastructural factors.

If the technology-developing country i cares only about the direct national benefits and only sees the export as a "by-product", that is, without taking into account how a specific γ will affect the export potential ($b_i^{ID}\left(T_j^{Total}\right)$), then this country would choose the technology that maximises:

$$\gamma_i^{BF} = argmax\{b_i^N\left(T_i(\gamma_i)\right) - IC_i\left(T_i(\gamma_i)\right) - c_i\left(T_i(\gamma_i)\right)\}$$

On the other hand, if the technology-developing country would be interested in maximising the diffusion of a technology, it should take the specific circumstances in the adopting country into account. Define $NB_j\left(T_j(\gamma)\right) = b_j^D\left(T_j(\gamma)\right) - c_j(T_j(\gamma))$ as the net benefit for country j of adopting the technology based on the technology's specification, γ. The best fit factors, γ_j, is defined as:

$$\gamma_j^{\mathrm{BF}} = argmax\{NB_j\left(T_j\left(\gamma_j\right)\right) = b_j^D\left(T_j\left(\gamma_j\right)\right) - c_j\left(T_j\left(\gamma_j\right)\right)\}$$

A technology that has the exact specification of γ_j will be the best fit technology for that specific country, not for other countries.

In particular, we will assume that $\gamma_i^{BF} \neq \gamma_j^{\mathrm{BF}}$ and that:

$$NB_j\left(T_j\left(\gamma_j^{\mathrm{BF}}\right)\right) > NB_j\left(T_j\left(\gamma_i^{BF}\right)\right)$$

$$NB_i\left(T_i\left(\gamma_i^{\mathrm{BF}}\right)\right) > NB_i\left(T_i\left(\gamma_j^{BF}\right)\right)$$

An important feature of a partnership is bridging the limitation of diffusion. This builds on the theory and observations that technology knowledge diffusion is faster in a country with a shared common language and where inventors communicate regularly etc. A partnership between two countries can therefore achieve a range of advantages when using the results from Klarl [42] and applying the same logic between countries because knowledge diffusion is faster when two countries interact directly, learn a "shared common language", and engage in regular direct communication.

A partnership should focus on a shared learning process. We model this as defining a joint specification vector γ_{ij} that includes learning and knowledge based on both countries' specific circumstances in ways that benefit both. To illustrate the following points, we re-write the net-benefit function as:

$$NB_i\left(T_i(\gamma)\right) = NB_i^D\left(T_j\right) + b_i^{ID}\left(T_j^{Total}(\gamma)\right)$$

$$NB_i^D\left(T_j\right) = b_j^D(T_j) - c_j(T_j)$$

An effective partnership should be able to focus on finding a technology based on shared knowledge and circumstances:

$$\gamma_{ij}^* = argmax\{NB_i^D\left(T_i(\gamma)\right) + b_i^{ID}\left(T_j^{Total}(\gamma)\right) + NB_j\left(T_j(\gamma)\right)$$

Creating a win–win situation (compared to $\gamma = \gamma_i^{BF}$) is defined as:

$$\mathrm{ConditionP1}: NB_i^D\left(T_i\left(\gamma_{ij}^*\right)\right) + b_i^{ID}\left(T_j^{Total}\left(\gamma_{ij}^*\right)\right) > NB_i^D\left(T_i\left(\gamma_i^{BF}\right)\right) + b_i^{ID}\left(T_j^{Total}\left(\gamma_i^{BF}\right)\right)$$

$$\mathrm{ConditionP2}: NB_j\left(T_j\left(\gamma_{ij}^*\right)\right) > NB_j\left(T_i\left(\gamma_i^{BF}\right)\right)$$

$$\underbrace{NB_i^D\left(T_i(\gamma_i^{BF})\right) - NB_i^D\left(T_i(\gamma_{ij}^*)\right)}_{\text{Loss from partnership in terms of direct benefits}} < \underbrace{b_i^{ID}\left(T_j^{Total}(\gamma_{ij}^*)\right) - b_i^{ID}\left(T_j^{Total}(\gamma_i^{BF})\right)}_{\text{Gain from partnership in terms of indirect benefits}}$$

Fig. 5 Trade-off for the technology-developing country when deciding on engaging in a partnership

From a learning perspective, the results show that maximising the likelihood that the technology will be adopted by a specific country, j, will need a consideration of the best-fit specification of the technology for that country, γ_j, and at the same time provide as much incentive in the first country to develop that technology. In the case of Denmark and China, a successful partnership would imply that the developing technology vector γ_{DK} can be combined with γ_{China} to $\gamma_{DK/China}$. Thus, it is possible to increase the probability that the follower will adopt the technology.

Note from Fig. 4 and condition 1 that tailoring technology to another country in itself will reduce the direct benefits in the developing country, but it will still increase the environmental benefits and the indirect benefits if it can harvest a major share of the spillovers, which is highlighted in Fig. 5. This is the real strength of a win–win partnership.

Hence, a partnership between Denmark and China, for example, has several positive effects by providing an ideal mechanism to accelerate wind turbine technology diffusion between the two countries. This will increase the cost-threshold in China, which means that less cost reduction is needed for China to adopt the technology as it has a better fit yielding more local benefits and providing the technology-developing country with large opportunities that would be lost without such a partnership. This brings us to the third condition for an effective partnership: the total adoption of the technology is increased due to the partnership, and it is defined as:

$$\text{ConditionP3}: \sum_{j \neq i} T_j\left(\gamma_{ij}^*\right) > \sum_{j \neq i} T_j\left(\gamma_i^{BF}\right)$$

Note that this does not necessarily imply that there is a net positive effect on emissions as the new technology could substitute other types of RES. However, it is unlikely that this is the case to a full extent. Therefore, satisfying condition P3 will also imply that the partnership will have the effect of reducing the global CO_2 emissions.

5 Conclusion

The main research question addressed whether a small green technology-developing country can increase technology diffusion to developing countries in climate action. The main answer is yes. As argued theoretically and in the case of the Danish-Chinese partnership, such collaboration can trigger win–win situations. A transfer of wind power technology from Denmark to the world's largest CO_2 emitter, China, helps reduce China's fossil-based energy consumption in a decentralised way. Hence, upscaling and an earlier transition to renewable energy address an immediate policy concern and may lead to more sustainable economic development in other developing countries.

The theoretical leader–follower model showed how such a partnership should provide the technology-developing country with a larger total net benefit than without the partnership. This result is related to the observation that a country often has a variety of objectives, and pursuing those objectives yield what could seem as indirect but still significant benefits stemming from reduced climate change (attributed to the diffusion of the CO_2-reducing technology as well as political and reputational benefits). Likewise, the receiving developing country also ends up with a best-fit technology that results in larger total net benefits than without the partnership, including local co-benefits and spillover effects. As a consequence, the partnership increases technology diffusion to developing countries. Thus, a partnership could be a meaningful shared platform to improve and tailor the technology towards such objectives.

Through such a learning process, technology diffusion could be further accelerated. Promoting green industries in developing countries would accelerate the transition from fossil fuel-based energy sources to non-fossil energy sources, and a booming market would also encourage even more innovation. Furthermore, the new and strong green industrial interests in developing countries would actively lobby to protect and expand their markets. These new green industries may also try to form unconventional coalitions with other stakeholders, such as environmental organisations in developing countries that also lobby for climate action.

In perspective, the EEAS has stated that more partnership initiative is needed in the future to solve collective action problems and should be designed "…to overcome this limitation of the EU's ability to engage internationally in the most effective way [and] allow [it] to pursue agendas beyond development cooperation with new powers, but also enable [it] to defend the core EU agenda globally with any other partner country if the need arises" [52], 22). Furthermore, the EEAS calls for more climate action specifically in developing countries [55]. If China, and developing countries in particular, can benefit from the partnership initiative, an effective tool has been found that can scale and contribute significantly to a more efficient global climate and energy policy in the future, such as European public policies that aim to achieve the Paris target level and avoid negative impacts of climate mitigation action.

Thus, these partnership initiatives between technology-developing countries and developing countries can potentially create even more decentralised win–win situations worldwide. Even small-scale initiatives may eventually trigger "trim tab effects" and assist the "large ships"—such as China, India, and Brazil—in setting the right course for climate action and sustainable economic development in developing countries.

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Declarations

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