IDENTIFYING INACCESSIBLE GHG-EMISSION-REDUCTION TECHNOLOGIES

In the context of decarbonisation, ambition and Article 6 of the Paris Agreement

Silke Mooldijk

MSc thesis in Climate Studies

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Supervised by Prof. dr Niklas Höhne

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Supervisors
Prof.dr Niklas Höhne (ESA)
Email: niklas.hoehne@wur.nl

Aki Kachi (NewClimate Institute)
Email: a.kachi@newclimate.org

Examiners
Prof.dr Niklas Höhne (ESA)

Prof.dr Rik Leemans (ESA)

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Summary

The 2015 Paris Agreement sets the ambitious target of limiting global temperature increase to well below 2ºC, pursuing efforts to limit the increase to 1.5ºC. This goal requires that global greenhouse gas emissions peak as soon as possible and that emissions reach net-zero by 2050. Consequently, all countries and sectors must decarbonise. Indeed, the Paris Agreement requires all countries to set domestic emission-reduction targets in their Nationally Determined Contributions (NDC). These NDCs are to be updated regularly and to reflect countries' highest possible ambition.

Further, Article 6 of the Paris Agreement provides countries with the possibility to use market mechanisms to increase ambition in their mitigation efforts. Although the Agreement does not define 'ambition', the term likely implies that countries can only sell emission-reduction units from 'inaccessible technologies'. For the purpose of this thesis, 'inaccessible technologies' are technologies that are immature and too expensive for a country to acquire without international support. Moreover, because the 1.5ºC temperature target requires rapid decarbonisation, purchasing countries should not use Article 6 to offset domestic emissions, especially not when these offsets were realised using accessible technologies.

In my thesis I developed a methodology to identify inaccessible technologies and I applied the methodology to two cases: net-zero energy buildings in Colombia and ground source heat pumps in Mongolia. The methodology can be used by potential host countries and project developers to determine whether international finance is necessary to implement certain technologies and whether Article 6 would be the best source to get such finance.

Based on literature, I selected two indicators that determine accessibility: technology maturity and costs. I assessed 'technology maturity' by looking at market penetration rates in the host country, in the region and in the country where the assessed technology is best developed. 'Costs' were assessed by calculating upfront and total costs. Next, I attached appropriate weight to each (sub-)indicator, using expert judgement. To make the indicators comparable, I normalised them on a scale of 0 to 10, where a low score indicates inaccessibility and a high score accessibility.

I found that net-zero energy buildings are likely inaccessible to Colombia, caused by high upfront costs and low technology maturity in the region and in Colombia. However, because total costs were just slightly higher than total costs for a standard building, alternative finance sources are likely a better option than Article 6. If Colombia would finance net-zero energy buildings with a loan or grant, the country would be able to count the associated emission-reduction units towards its domestic NDC target. Further, I found that ground source heat pumps are likely inaccessible to Mongolia, because of high upfront and total costs and low technology maturity in Mongolia and neighbouring countries. Accordingly, Article 6 is probably one of the few financial sources available to Mongolia.

The limitations of my research involve the missing data on costs of NZEBs in Colombia and the threshold for costs. This threshold influences the indicator's score. I addressed the latter point by

considering various thresholds in my research and analysing their influence on the final result. I found that, in the two case studies, using different thresholds did not, or not substantially, change the accessibility scores. Further, to overcome the barrier of missing data, I approximated the missing NZEB data from the costs of building components in other countries and used conservative estimates.

In conclusion, the methodology that I developed in my thesis, concludes that net-zero energy buildings in Colombia and ground source heat pumps in Mongolia are likely inaccessible to these two countries. While Article 6 finance is a good option for Mongolia, Colombia should explore other finance sources, so associated emission-reductions can count towards its own NDC target.

List of abbreviations

CDM	Clean Development Mechanism
CMA	Conference of Parties serving as the Meeting of the Parties to the Paris Agreement
COP	Conference of the Parties
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
IPCC	Intergovernmental Panel on Climate Change
ITMO	Internationally Transferred Mitigation Outcome
LCOE	Levelised Costs of Energy
LCOH	Levelised Costs of Heat
MAC	Marginal Abatement Cost
NDC	Nationally Determined Contribution
NPV	Net Present Value
NZEB	Net-Zero Energy Building
OMGE	Overall Mitigation in Global Emissions
PV	Photovoltaic
RQ	Research Question
SIDS	Small Island Developing States
TRL	Technology Readiness Levels
UNFCCC	United Nations Framework Convention on Climate Change
VSL	Value of a Statistical Life

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1 Introduction

In December 2015 the Conference of Parties (COP) to the United Nations Convention on Climate Change (UNFCCC) adopted the Paris Agreement, which aims to limit the global average temperature increase to well below 2ºC and to pursue efforts to limit the increase to 1.5ºC, compared to pre-industrial levels (Paris Agreement, Article 2(1)). This 1.5 ºC target requires global emissions to be net-zero by 2050, which in turn demands rapid decarbonisation of all sectors and economies worldwide (IPCC, 2018).

Article 6 of the Paris Agreement provides that countries can engage in the voluntary transfer of emission reductions to allow for higher ambition in their mitigation and adaptation actions. Such transfers are not a novel concept. Indeed, the Kyoto Protocol provided for the possibility of three market mechanisms, including the Clean Development Mechanism (CDM). Industrialised countries with greenhouse gas (GHG) emission-reduction targets under the Kyoto protocol (the so-called Annex-I countries) could finance emission-eduction projects in developing countries and use the associated GHG-emission reductions towards their own targets. This construction allowed the increase of domestic GHG emissions in Annex-1 countries, as long as those emissions were offset under the CDM.

However, for various reasons emissions trading and offsetting do not work the same under the Paris Agreement as under the Kyoto Protocol. First, whereas under the Kyoto Protocol only industrialised countries had emission-reduction targets, the Paris Agreement requires *all* countries to prepare Nationally Determined Contributions (NDCs) and set emission-reduction targets. Second, the Paris Agreement temperature goals require GHG emissions to peak as soon as possible and require complete decarbonisation by 2050, which means that all countries must reduce their emissions rapidly. As a consequence, it is no longer an option for countries to offset domestic emissions in other countries. Third, Article 6 explicitly aims at raising ambition. Although the text of the Paris Agreement is not clear on the meaning of 'ambition', the term likely implies that Parties can only trade emissions if this results in GHG emission abatement beyond NDC targets. For these three reasons, countries should not sell emission reductions that are cheap or easy to achieve, but rather reductions that require expensive or otherwise inaccessible technologies (NewClimate Institute, 2018). Moreover, by focusing on the 'high-hanging fruit', instead of on accessible technologies, host and purchasing countries can help achieve transformational change. Such change in needed to reach the Paris Agreement temperature goals (Schellnhuber, Rahmstorf, & Winkelmann, 2016).

Thus, countries should only engage in trading emission-reduction units when then the technologies used to achieve these reductions are not accessible to the host country. However, it is not yet clear how to identify 'inaccessible technologies', so in my thesis I aim to provide a methodology to determine whether technologies are inaccessible. To that end, I answered the following four research questions (RQ):

1) What does the Paris Agreement provide with regard to emission trading and how does this differ from provisions under the Kyoto Protocol?
2) In addition to Article 6 of the Paris Agreement, what other finance sources are available to countries that want to acquire inaccessible technologies and when should countries opt for what finance source?
3) What could be a methodology to identify ‘inaccessible technologies’?
4) How would net-zero energy buildings (NZEB) in Colombia and ground source heat pumps (GSHP) in Mongolia be classified when applying this methodology?

Chapter 2 of this thesis outlines the methods that I used to answer the four research questions. In this Chapter I also answer RQ 3 and explain what methodology I developed to identify ‘inaccessible technologies’. In Chapter 3, I answer RQ 1 and 2 and outline the goals and implications of the Paris Agreement, specifically regarding to ambition and Article 6 and on carbon trading. This information helps the reader understand the rationale for this thesis. Chapter 4 outlines the indicators for ‘inaccessibility’, which I selected based on a literature study. I present case studies on NZEBs in Colombia and ground source heat pumps in Mongolia in Chapters 6 and 7, respectively. Chapter 8 discusses the results of my thesis. Finally, Chapter 9 concludes.

2 Methodology

In this thesis I seek to answer the following four research questions:

1) What does the Paris Agreement provide with regard to emission trading and how does this differ from provisions under the Kyoto Protocol?
2) In addition to Article 6 of the Paris Agreement, what other finance sources are available to countries that want to acquire inaccessible technologies and when should countries opt for what finance source?
3) What could be a methodology to identify inaccessible technologies?
4) How would NZEBs in Colombia and GSHPs in Mongolia be classified when applying this methodology?

For the purpose of this thesis, ‘technologies’ are defined as tools and practices. I understand ‘inaccessible technologies’ to be technologies that do not discourage further NDC ambition because they are too costly or novel for the host country to employ by itself. If countries would be allowed to sell emission reductions achieved by using accessible technologies, countries have an incentive to set low NDC targets, leading to lower GHG-emission-reduction levels. In other words, the implementation of inaccessible technologies places countries on an emission trajectory beyond the NDC targets. This contributes to more ambition, as required by Article 6 of the Paris Agreement. To answer research RQ 1 and 2 a literature review was conducted. I used the key words ‘Paris Agreement’, ‘Article 6’, ‘Kyoto Protocol’, ‘carbon trading’, ‘emissions trading’, ‘climate finance’, ‘grant’, ‘multilateral development bank’ and ‘Green Climate Fund’ on Google Scholar and Wageningen University’s online library catalogue to find relevant academic, peer-reviewed articles. Moreover, I analysed the text of the Paris Agreement and draft decisions by the Subsidiary Body for Scientific and Technological Advice, which is one of the two permanent subsidiary bodies to the UNFCCC.

To answer RQ 3 and 4, I took the following seven steps: selection of indicators that identify accessibility; attaching weight to each indicator; determine thresholds for when technologies are mature and when costs become too expensive for the host country; data collection to assess technology accessibility for the two case studies; data normalisation on a scale from 0 to 10; determining the accessibility score for NZEBs in Colombia (Cartagena) and GSHPs in Mongolia (Khovd); and finally performing a sensitivity analysis (Figure 1). In the remainder of this Chapter, I explain these seven steps in more detail.

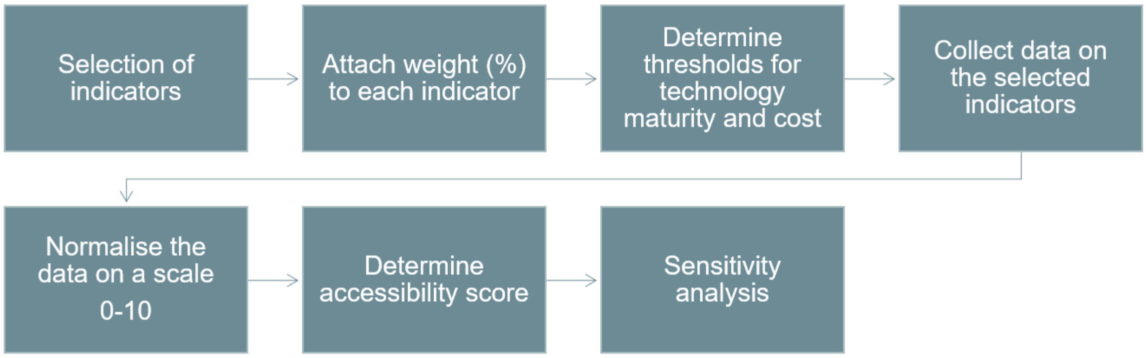

Figure 1. Methodology process

2.1 Selection of indicators

I conducted a literature review to identify indicators that determine whether a certain technology is accessible to a host country (see Chapter 4). For the purpose of this thesis, indicators should be understood as barriers that hinder a country in obtaining a technology. To find peer-reviewed papers on barriers to the uptake of (new) technologies, I used the key words 'barrier', 'uptake' and 'technology' on Google Scholar and Wageningen University's library catalogue.

Based on the literature describing different barriers to the implementation of technologies, I selected the following indicators and sub-indicators for inaccessibility:

1) Technology maturity
    a. Market penetration in the host country (%);
    b. Market penetration in the region (%); and
    c. Market penetration in the country where the technology is best developed (referred to as best practice) (%)
2) Costs
    a. Upfront costs, compared to the costs associated with technologies currently used (%); and
    b. Lifetime costs of the technology, compared to the costs of the technologies currently used (%)

The lifetime costs of the technology were calculated at present value, which is the current value of future cash flows. In my case studies I used discount rates of 5% (Colombia) and 8.75% (Mongolia), which are equal to the interest rates of government bonds. To assess the influence of the discount rate, I also calculated present value with discount rates of 0% and 10% for both case studies and 5% for Mongolia. Chapter 4 contains more detailed information on these indicators and a justification for selecting them, based on a literature review. In that Chapter I also discuss why I selected only 'technology maturity' and 'costs' as indicators and excluded other factors that influence technology accessibility.

2.2 Attaching weight values to the indicators

I attached appropriate weight to each (sub-)indicator based expert judgement. The weight values range between 0 and 100% and the weight of the two indicators combined is 100%. Figure 2 provides an overview of the different indicators and sub-indicators. Costs and technology maturity are considered equally important in determining accessibility, because both high costs and low maturity can hinder the uptake of a technology (see Chapter 4). The sub-indicators 'upfront costs' and 'total costs' also receive equal weight. The sub-indicators 'market penetration domestically' and 'market penetration regionally' are considered more important than the sub-indicator 'market penetration best practice', because the former two provide information of the technical capabilities and know-how of local engineers and technicians, as well as the suitability for the technology regarding the host country's geographic characteristics.

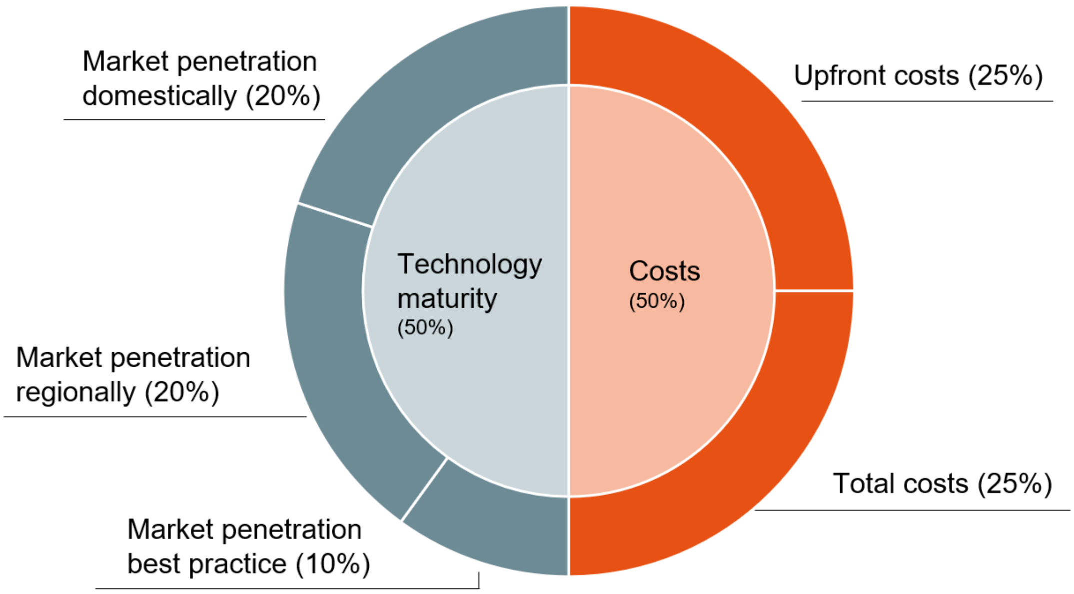

Figure 2. Indicators and sub-indicators to determine inaccessibility, with between brackets their weight

2.3 Determine thresholds for technology maturity and costs

The development status and wealth of a country determine to a large extent how much a country can spend on additional measures to reduce GHG emissions. The World Bank's country income classification divides the world's countries in four different groups: from low-income (GNI per capita lower an 996 USD) to high-income countries (GNI per capita higher than 12,055 USD). I used this index to set different costs thresholds for different income groups (Table 1). I assumed low income countries have only a small budget available to spend on new technologies, but lower-middle and upper-middle income countries could spend two and four times as much as the costs of currently used technologies. Finally, high-income countries should be able to spend 15 times as much as the costs of technologies that are currently used in those countries.

Table 1. World Bank income classification (as of June 2018) and thresholds

Income group	GNI per capita (in current USD)	Threshold at which costs become too expensive (% of current costs) (thresholds for sensitivity analysis)
Low income	<995	120% (110%, 150%)
Lower-middle income	996-3,895	200% (150%, 300%)
Upper-middle income	3,896-12,055	400% (200%, 600%)
High income	>12,055	1500% (500%, 2500%)

2.4 Normalisation of indicators

In order to make the indicators comparable, I normalised them on a scale of 0-10, where a low score indicates inaccessibility and a high score accessibility. I used the following formula (Equation 1) to normalise each indicator, following Nardo *et al.* (2008) and based on NewClimate Institute, Germanwatch and Allianz SE (2018):

$$X_{i(nom)} = 10 \cdot \frac{(X_i - X_{worst})}{(X_{best} - X_{worst})} \qquad \text{(Equation 1)}$$

Where $X_{i(nom)}$ is the normalised value of indicator *X*; X_{worst} is the lower boundary at which technologies would be inaccessible in terms of maturity or costs (i.e. low maturity and high costs) and X_{best} the upper boundary at which technologies are accessible (i.e. high maturity and low costs).

Regarding the indicator ‘technology maturity’, I assigned market penetration rates of and above 16% with a 10 (i.e. definitely accessible). I based the 16% threshold on Rogers’ Theory of Diffusion (1971), which shows that generally technologies with a penetration rate above 16% are taken up by the majority of consumers (see Section 4.2).

Regarding the indicator ‘costs’, an important question is when costs become so high that they render a technology inaccessible for the host country. To answer this question, a baseline must be set as a reference point for comparison. In this inaccessibility framework, the costs of currently used technologies, for instance coal-fired power plants or natural gas, are the baseline. Host countries are able to bear the costs related to those technologies, so technologies that are as expensive or cheaper should not be inaccessible due to their costs.

Further, the thresholds in Table 1 show at what point the technology becomes too expensive for a host country. I assumed the cost level at and above these thresholds as inaccessible and therefore those costs received a 0, whereas costs lower than or equal to current costs receive a 10 (accessible). Costs in between the upper bound (X% the costs of the costs of the current technology) and the lower bound (as expensive or cheaper than the current technology) would receive a score between 0-10, using the formula in Equation 2. This equation is slightly different from equation 1 to account for the fact that the higher the costs are, the lower the accessibility score should be. Therefore, I subtracted the outcome of Equation 1 from 10 (which indicates 'accessibility') to get the accessibility score for costs (Equation 2).

$$X_{i(nom)} = 10 - \left(10 \cdot \frac{(X_i - X_e)}{(X_t - X_e)} \right) \qquad \text{(Equation 2)}$$

Where X_i reflects the costs of the assessed technology expressed in percentages compared to the existing technology's costs (i.e. if total costs of the existing technology amount to 100 USD and the total costs of the new technology to 450 USD, X_i is 450). X_e are the existing costs, expressed as 100. X_t is the threshold at which costs become too expensive for the host country (e.g. if the new technology's costs are 120% of the current technology's costs, X_t is 120).

When the new technology exceeds the threshold or is cheaper than the current technology, the outcome of Equation 2 lies below 0 or above 10. Because 0 reflects complete inaccessibility and 10 complete accessibility, I truncated negative scores to 0 and scores higher than 10 to 10.

The methodology described above can be used to assess technologies for their accessibility. Each technology receives an accessibility score between 0 and 10, where 0 indicates that a technology is inaccessible and thus potentially suitable for Article 6 intervention and a score of 10 would indicate the technology is easily accessible to the host country and that Article 6 should not be used.

Rather than establishing a strict threshold below which technologies would be inaccessible, for instance at a score of '4' or '6', I used a sliding scale. The reason for this is that the weight attached to the indicators is subjective, as are the thresholds used to determine whether costs associated with a certain technology are too expensive for the host country. By assigning a score, however, host countries, acquiring countries and project developers can get a good indication of whether or not a certain project is suitable for Article 6.

2.5 Case studies

Using this methodology, two case studies were conducted in which I determined whether NZEBs and GSHPs would classify as inaccessible in Colombia and Mongolia, respectively. Both these countries have hosted various CDM projects in the past and are potential Article 6 host countries, which makes them interesting case studies.

Colombia is an upper-level middle income country (World Bank, 2018). In 2015, the residential sector consumed 17% of total energy demand (UPME, 2017). Replacing standard social housing apartment blocks with NZEBs is very likely to substantially reduce GHG emissions, because NZEBs need considerably less energy than standard buildings (BPIE, 2011). Moreover, the proposed project installs solar photovoltaic (PV) panels to cover the energy demand that NZEBs still have. Hydropower generates a large share of Colombia's energy demand (Arias-Gaviria, van der Zwaan, Kober, & Arango-Aramburo, 2017), so the country has a relatively clean energy grid. However, Wang *et al.* (2014), have shown that hydropower reservoirs emit significant amount of methane, which is a potent GHG. For this reason, it is preferable to equip the NZEBs with solar PV, rather than connect them to the existing electricity grid.

Mongolia is a lower-level middle income country (World Bank, 2018) and heavily dependent on coal, which accounts for 96% of the total fuel utilisation (Ministry of Environment and Tourism, 2018) In addition to district heating, many households burn coal in small stoves to heat their houses. As a result, air pollution is a major problem in Mongolian cities, leading to an estimated 2,400 deaths per year (The World Bank; & Institute for Health Metrics and Evalution, 2016). Ground source heat pumps would not only substantially reduce GHG emissions, but also improve air quality in Mongolia. This makes replacing coal-fired heat plants with GSHPs a particularly interesting option.

The two case studies required data on current energy prices; project costs of technologies that are currently used and of alternative technologies; lifespans of current and proposed technologies, market penetration rates of alternative technologies etc. I collected this data from various sources, including a peer-reviewed study on the costs of heat pumps (Nian, Sun, Ma, & Li, 2016), studies by the Global Green Growth Institute on heat pumps in Mongolia (GGGI, 2018; GGGI & Government of Mongolia, 2016b, 2016a) and the natural gas and electricity providers in Colombia. Figure 3 shows the methodology process for each case study. First, I determined the development status of Colombia and Mongolia. Second, I collected data on the two indicators (technology maturity and costs) in both countries from a variety of sources. For the Colombian case study, data on costs include costs of developing and building an NZEB; maintenance costs of PV panels (purchasing and instalment costs are included in the cost assessment of the NZEB); and data on electricity and gas consumption and tariffs.

In the case study on GSHPs in Mongolia, I did three cost assessments: costs of the existing coal-fired heat plants, costs of installing heat pumps for all residential buildings that are currently connected to the district heating grid and costs of the GSHPs considering public health co-benefits associated with decreased air pollution. For the third cost assessment, I collected estimations on the co-benefits per tonne of CO2. Since these estimations were unavailable for Mongolia, I used estimations for China, as provided by Nemet, Holloway and Meier (2010) and West *et al.* (2013).

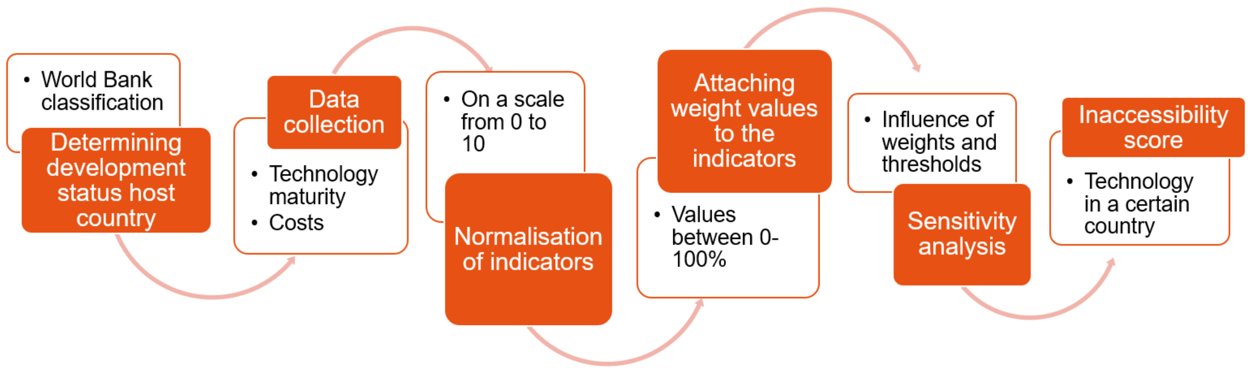

Figure 3. Methodology process case studies

2.6 Sensitivity analysis

Finally, after I had calculated the accessibility scores for NZEBs in Colombia and GSHPs in Mongolia, I applied a sensitivity analysis to assess the influence of the different indicators on the final accessibility score (Loubière, Jourdan, Siarry, & Chelouah, 2018). I changed the discount rates that were used in both case studies to calculate total costs; the relative weight attached to the indicators; and the thresholds determining when costs become too expensive for host countries. I opted for a sensitivity analysis and not for an uncertainty analysis, because I wanted to assess the different indicators' influence on the accessibility score of NZEBs and GSHPs, rather than to quantify the uncertainty range of these scores.

3 Emission trading under the Paris Agreement and alternative climate finance sources

In this Chapter I answer the following two research questions:

1) What does the Paris Agreement provide with regard to emission trading and how does this differ from provisions under the Kyoto Protocol?
2) In addition to Article 6 of the Paris Agreement, what other finance sources are available to countries that want to acquire inaccessible technologies and when should countries opt for what finance source?

First, I briefly explain the concept of emissions trading. Second, I outline the Paris Agreement's goals and the obligations the Agreement lays down for Parties. In Section 3.3 I discuss Article 6 of the Paris Agreement and the relationship between provisions on carbon transfer in the Paris Agreement and the Kyoto Protocol. In Section 3.43.5 I discuss the implications of the Paris Agreement's provisions for the international transfer of emission-reduction units. Further, in Section 3.5 I answer the second research question and explain what finance sources for 'inaccessible technologies' exist. Finally, in Section 3.6 I conclude by summarising the answers to the two research questions above.

3.1 Emissions trading

GHG emissions are a good example of an externality: the consequences of an economic activity that affect a third party and are not naturally priced (Grubb, 2013). In 1920, Pigou proposed to put a tax on externalities in order to internalise the environmental costs of pollution into private decisions (Pigou, 1920). Forty years later, Coase challenged this proposition and argued that externalities could best be regulated by creating entitlements to pollute. These entitlements are based property rights. Accordingly, participants in the market will bargain and the participant who values the entitlement most, obtains it (Coase, 1960). In theory, emission markets lead to cost minimisation, because the emission reductions take place where it is cheapest to do so. In the 1990s, emission trading schemes for SO_2 and NO_X were set up in the United States (Burtraw, Evans, Krupnick, Palmer, & Toth, 2005). More recently, various jurisdiction have created trading schemes for GHG emissions (Redmond & Convery, 2015), of which the European Union Emissions Trading Scheme is the largest.

3.2 Paris Agreement goals and obligations

The Parties to the Paris Agreement agreed to hold the global average temperature increase to well below 2ºC above pre-industrial levels and to pursue efforts to limit the increase to 1.5ºC (Article 2.1). Small-Island Developing States (SIDS) had advocated for a 1.5ºC long-term goal for years, but major negotiating blocks largely ignored these efforts (Doelle, 2016). Therefore, the inclusion of the 1.5ºC goal came unexpected to many and is perhaps the main accomplishment of the Paris Agreement. Since COP21 in Paris, the 1.5ºC target has become the standard against which climate efforts are to be assessed (Doelle, 2016), especially after the IPCC released its Special Report on Global Warming of 1.5ºC, which shows that climate-related risks for natural and human systems are lower at 1.5ºC than at 2ºC (IPCC, 2018). Limiting global average temperature increase to 1.5ºC requires GHG emissions to be net-zero around 2050 (IPCC, 2018). Different pathways are possible to reach this goal, but the Paris Agreement recognises that besides peaking emissions as soon as possible and undertaking rapid reductions thereafter, removal of GHGs from the atmosphere is likely necessary (Article 4.1).

Countries are to collectively reach the 1.5ºC-temperature goal, based on the principle of common but differentiated responsibilities and respective capabilities (Article 2.2). In other words: countries have different implementation capacities (e.g. financial and technical resources) and also different historical responsibilities to reduce GHG emissions (UNFCCC preamble, Article 4.1; see also Gupta and Arts, 2018). Based on these different capacities and responsibilities, countries are to define emission-reduction targets in their Nationally Determined Contributions (NDCs). These NDCs are to be updated regularly (Article 4.2); to represent a progression of GHG reduction over time; and to reflect country's highest possible ambition (Article 4.3). Indeed, the need for high ambition is reiterated throughout the text. In addition to Article 4.3, the Paris Agreement also invites developed countries to support developing countries, so developing countries can increase ambition in their mitigation actions (Article 4.5); provides that countries may adjust their NDCs at any time to enhance their ambition level ambition (Article 4.11); and recognises that countries can cooperate to realise "higher ambition in their mitigation and adaptation actions" (Article 6.1).

The NDCs are a core element of the Paris Agreement (Rogelj et al., 2017) and should eventually collectively be sufficient to meet the long-term temperature goal (Doelle, 2016). The Global Stocktake, which is to take place every five years, is an important component in monitoring progress towards the long-term temperature goals (Höhne et al., 2017). Nonetheless, current pledges fall substantially short of meeting the 1.5ºC temperature goal. Policies currently in place are projected to limit global warming to 3.3ºC above pre-industrial levels and the unconditional pledges that governments made until December 2018 would limit global temperature increase to 3ºC (Climate Action Tracker, 2018).

3.3 Paris Agreement Article 6

Article 6 of the Paris Agreement recognises that countries may choose to "pursue voluntary cooperation in the implementation of their nationally determined contributions to allow for higher ambition in their mitigation and adaptation actions" (Article 6.1). The requirement of higher ambition likely implies that countries can use Article 6 activities only to achieve deeper emission reductions than outlined in their NDCs.

Article 6 provides three different options for cooperation:

1. **Article 6.2** provides for an overall framework for cooperative approaches, allowing countries to internationally transfer mitigation outcomes (ITMO). The text in the Paris Agreement does not specify how the use of ITMOs is to take place exactly. Transfers could for instance take the shape of linked Emission Trading Schemes or direct transfers on bilateral or multilateral basis (Marcu, 2016). Unlike the mechanism created under Article 6.4, the mechanism or procedure

which produces ITMOs does not necessarily need to operate under the auspices of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA).

2. **Article 6.4** establishes a new international market mechanism under the authority and guidance of the CMA. With this mechanism, Parties can contribute to GHG-emission reductions in a host country and use (part of) the reductions to their own NDC target. Unlike Article 6.2, Article 6.4 aims to deliver an overall mitigation in global emissions (OMGE) (Article 6.4.d). What exactly this means, however, is unclear. Schneider *et al.* (2018) recommend OMGE to be understood to be delivered when a portion of the emission-reduction units is not used by any country towards its NDC target. The final CMA draft agreement of COP24 (13 December 2018), includes the option of defining OMGE as achieved when "through the operation of Article 6, a fixed percentage of emission reductions, duly reported, are not used by any Party or entity to implement or achieve its nationally determined contribution (NDC) or used for any other compliance purposes outside Article 6." (Annex, II.1.c).
3. **Articles 6.8 and 6.9** establish a framework for non-market approaches to sustainable development with the aim to promote mitigation and ambition; enhance public and private sector participation in NDC implementation; and enable opportunities for coordination across instruments and relevant institutional arrangements.

Because Article 6.8 does not involve transfers of emission reductions, for the purposes of this thesis, only Articles 6.2 and 6.4 are relevant.

Although clear guidelines on both Articles are lacking, several differences between Article 6.2 and Article 6.4 are likely to exist (Table 2). These are the following: Article 6.4 provides a centralised mechanism, whereas Article 6.2 provides for a decentralised approach; Article 6.4 requires a share of proceeds to flow to developing countries that are particularly vulnerable to climate change; and Article 6.4 also provides that the transfer of emission-reduction units shall aim to deliver an "overall mitigation in global emissions".

However, both provisions may turn out very similar once guidelines are finalised. For instance, the draft CMA decision of 13 December 2018 "encourages" parties to deliver OMGE in the context of Article 6.2. Moreover, it includes the option that ITMOs are to cover emission reductions under the Article 6.4 mechanism (SBSTA, 2018). In their studies, La Hoz Theuer, Schneider and Broekhoff (2018) and NewClimate Institute (2018) also assumed that emission-reduction unita generated using the Article 6.4 mechanism can be used as ITMOs under Article 6.2. If the CMA would allow countries to transfer ITMOs under the Article 6.4 mechanism, this would blur the distinction between Articles 6.2 and 6.4.

Parties had planned to agree on further guidance for Article 6 at COP24 in Katowice as part of the overall Paris Agreement Rulebook, but consensus could not be achieved and the issue of adopting rules clarifying Article 6 was pushed to COP25 in November 2019.

Table 2. Differences between Article 6.2 and Article 6.4.

	Article 6.2	Article 6.4
OMGE	No explicit requirement for an overall mitigation in global emissions. However, the draft CMA decision of 13 December 2018 encourages countries to deliver an OMGE by voluntarily cancelling or setting aside ITMOs that are not used for any transfer or purpose (SBSTA, 2018).	The Article 6.4 mechanism "shall aim to deliver an overall mitigation in global emissions" (Article 6.4.d).
Share of proceeds	No share of proceeds.	Share of proceeds to cover administrative expenses and to financially support vulnerable developing country with their adaptation efforts.
Oversight body	De-centralised, meaning that the transfer of emission-reduction units does not follow a common procedure that is established by the CMA.	Centralised, meaning that the transfer of emission-reduction units is to take place under the authority and guidance of the CMA, following a common procedure.

3.3.1 Relationship Paris and Kyoto

Although no direct link between the Paris Agreement and its predecessor, the Kyoto Protocol, exist, cooperative approaches under Article 6.2 and Article 6.4 can be considered successors to the Joint Implementation (JI) and the CDM under the Kyoto Protocol. Under the JI, industrialised countries (so-called Annex-I countries) with emission-reduction targets could finance a GHG-emission-reduction project in another Annex-I. The associated reduction units count towards the target of the financing country. Likewise, under the CDM, Annex-I countries could finance projects in non-Annex I countries that had no targets and count the associated emission reductions to their own reduction targets. As such, the CDM provided countries with an alternative to expensive or politically difficult domestic emission reductions (Bumpus & Liverman, 2008).

Under the Paris Agreement, however, all countries are to set emission-reduction targets in their NDCs. Article 6 allows for the use of ITMOs to achieve NDCs (Article 6.2) and creates a mechanism "to contribute to the mitigation of greenhouse gas emissions" (Article 6.4). This mechanism is understood to be a market mechanism (see e.g. Olsen, Arens and Mersmann, 2018; Schneider and La Hoz Theuer, 2019). While the Paris Agreement does not explicitly prohibit countries from selling emissions when they have not yet achieved their NDC target, this situation is incompatible with the requirement of increased ambition (Article 6.1). Accordingly, countries should only sell those emissions that are not needed towards their NDC target. For instance, Mongolia has a baseline of a 110 tonnes CO2 in 2010 and aims to emit 80 tonnes in 2030 (i.e. a reduction of 30 tonnes CO2). Switzerland emitted 150 tonnes

CO2 in 2010 and sets a target of 50 tonnes in 2030 (i.e. a reduction of a 100 tonnes). If, in 2030, Mongolia overachieved its target and reduced 40 tonnes, it can sell 10 tonnes to a country that missed its own target. If Switzerland for instance emitted not 50 tonnes, but 60 tonnes of CO2 in 2030, it can buy reduction units for 10 tonnes CO_2 from Mongolia (Figure 4). As a result, both countries reach their target from an accounting viewpoint.

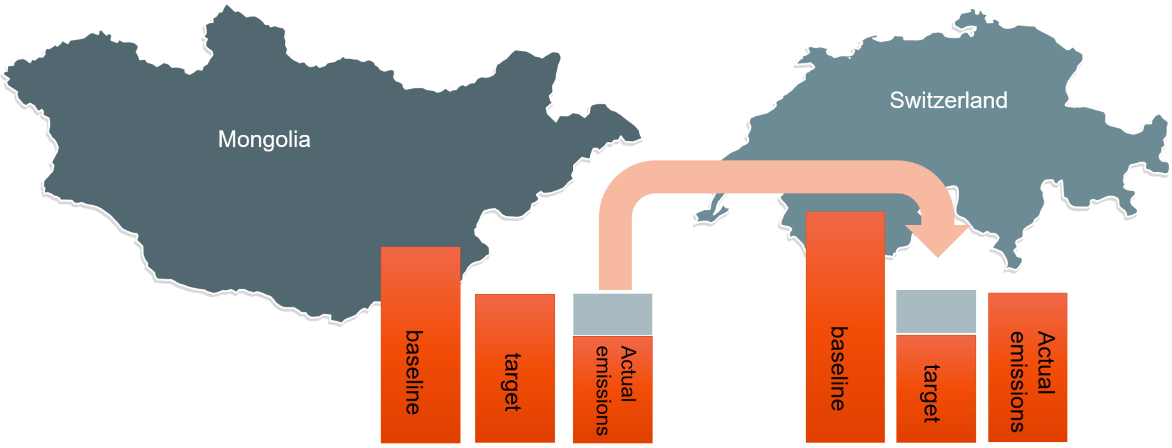

Figure 4. Emission trading between Mongolia and Switzerland.

3.4 Implications of high ambition and the 1.5ºC temperature goal for Article 6 activities

Parties to the Paris Agreement committed themselves to keeping global temperature increase well below 2ºC and to pursue efforts to limit the increase to 1.5ºC compared to pre-industrial levels. The likelihood of achieving the 1.5ºC goal is largest if global GHG emissions peak as soon as possible and are net-zero by 2050. In other words, all countries and sectors must decarbonise in the next three decades (IPCC, 2018). The Paris Agreement also requires countries' NDCs to be as ambitious as possible (Articles 4.3 and 4.11) and countries can use Article 6 to increase their ambition (Article 6.1). Accordingly, Parties should only sell emission-reduction units if they overachieve their most ambitious NDC target and Parties should only purchase such units in addition to the most ambitious possible domestic actions. This means that all countries have an incentive to keep the cheapest emission reductions for themselves. Furthermore, emission-reduction targets are to progress overtime, so opportunities for trading emissions diminish.

As there is only limited scope for the transfer of GHG emission-reduction units. This idea is rather novel and has not attracted any attention in academic literature. How to define 'inaccessibility' is the central issue of this thesis and will be further elaborated upon in the next chapters. Simply put, inaccessible technologies are immature and too expensive for the host country to purchase without foreign support. However, while Article 6 should only be used for inaccessible technologies, inaccessible technologies should not be financed by Article 6 activities per se. It is important that host countries consider whether inaccessible technologies can become accessible using finance from sources other than Article 6 activities. In the next Section I answer research question 2 and I outline what finance sources exist and when countries should opt for what source.

3.5 Alternative finance sources

While Article 6 can be attractive to host countries because it offers a source of income and the country profits from co-benefits from the GHG emission reduction, other, non-market-based, finance sources for GHG mitigation activities also exist (Jakob, Steckel, Flachsland, & Baumstark, 2015). These finance sources include loans from multilateral development banks, bilateral loans and grants from the Green Climate Fund (Steckel et al., 2017).

If potential host countries opt for finance sources other than Article 6, they can count associated emission reductions towards their own NDC target and potential acquiring countries have less opportunities to purchase international reduction units, so the need to focus on domestic emission reductions will be even stronger. Therefore, using other finance sources whenever possible, is preferable from both the host country perspective and the climate perspective. The decision tree in Figure 5 shows what finance source is preferable under what circumstances.

Article 6 finance would be an option for host countries in the following two scenarios:

1) The technology is immature in the host country and globally and has high total and/or upfront costs. The host country likely has difficulties finding a loan or grant, because the technology's results are unsure. Further, interest rates are likely to be high as a result of the high risk associated with implementing a novel technology. Moreover, if total costs are high and the payback period is long, this is likely a barrier to the host country to take out a loan; and
2) When the technology is mature globally, but total costs are so high that a host country will not be able to recoup the investment, Article 6 is a good alternative to other finance sources.

However, a loan or grant is likely the best option when the technology is mature globally and overall costs are relatively low, but upfront costs are relatively high. The big advantage of taking out a loan rather than Article 6 finance, is that the host country can count the associated GHG emission-reduction units toward its own target. Moreover, the less opportunities (developed) countries have to offset their emissions abroad, the more likely these countries are to further invest in the reduction of domestic emissions.

Finally, if the technology is immature, both at a domestic and global level, but total and/or upfront costs determining what source of finance is best, requires further analysis. Depending on the host country's development status and budget; the level of technology maturity and the level of costs; etc various finance sources could be preferable.

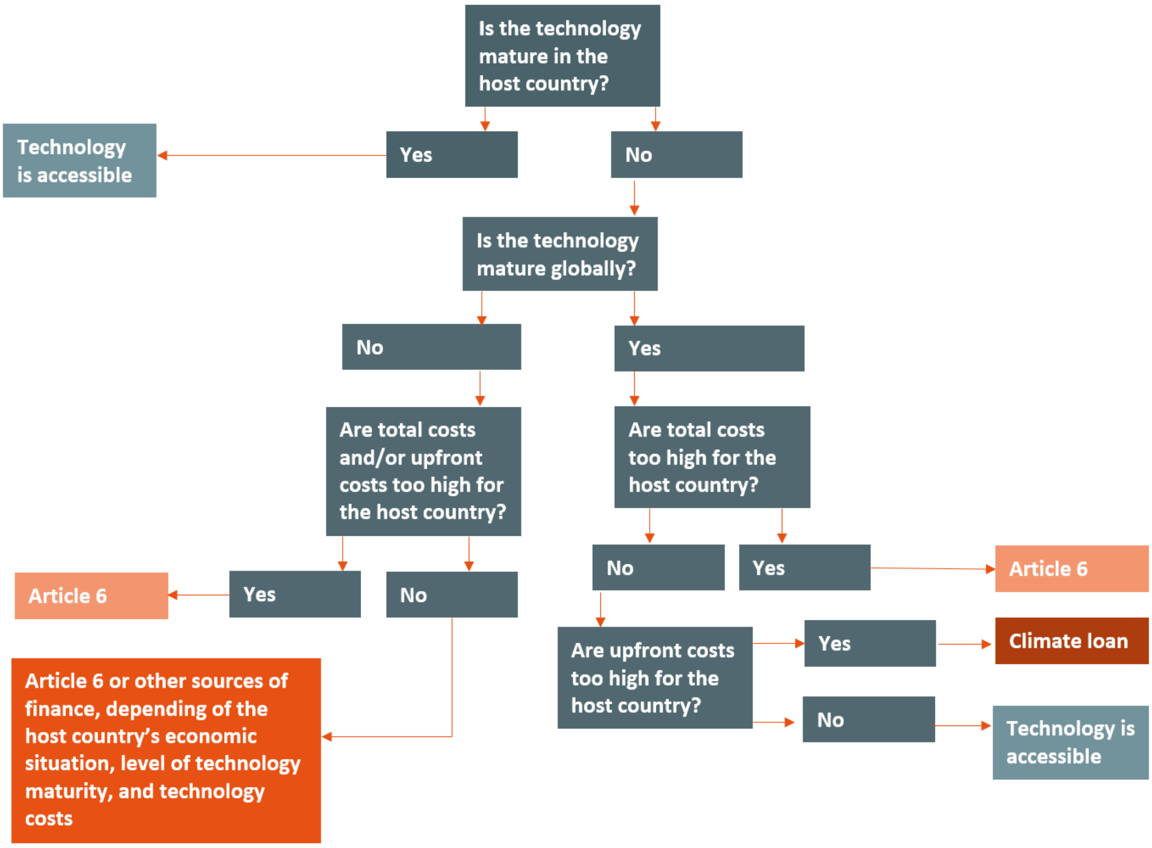

Figure 5. Decision tree for finding finance for inaccessible technologies

3.6 Conclusion of research questions 1 and 2

The Paris Agreement allows Parties to trade emission-reduction units to increase ambition in mitigation actions. The key differences between the pre- and post-Paris era are the following:

1) The Paris Agreement requires all countries to set ambitious emission-reduction targets in their NDCs;
2) The 1.5 ºC limit requires net-zero emissions by 2050, so all countries and sectors must decarbonise in the next three decades;

Accordingly, the scope for either selling or purchasing emission-reduction units is very limited. Host countries need reduction units to reach their domestic NDC target and purchasing countries should focus on reducing domestic emissions to reach net-zero emissions by 2050. For these reasons, Article 6 of the Paris Agreement should only be used to finance 'inaccessible technologies'. Nevertheless, inaccessible technologies should not be financed by Article 6 activities per se as other finance sources exist. These include for instance loans and grants from multilateral development banks or the Green Climate Fund. When countries finance 'inaccessible technologies' with alternative finance sources, they can count the associated emission-reduction units towards their own NDC. For this reason, alternative finance sources are preferable from both the host country and climate perspective, and Article 6 should only be used as a measure of last resort.

4 Indicators

In this Chapter, I discuss the results of my literature study looking at the barriers to the implementation of low-carbon technologies. I find there are two main barriers: technology maturity and costs, which I selected as the two indicators of 'inaccessibility'. In Sections 4.24.3, I outline how these two factors hinder the implementation of new technologies and why I selected them as indicators. Further, in Section4.4 I explain why three other factors that help drive 'inaccessibility' are not included in my methodology.

4.1 Barriers to the implementation of low-carbon technologies

Various factors play a role in the diffusion of new technologies, including the costs associated with the technology; actors and their competences, both technical and other forms of competence; and institutions and policies (Jacobsson & Johnson, 2000). New technologies face a number of barriers to their uptake. The most important barrier is the cost of the technology, in particular the private costs borne by the actor implementing the technology. This actor could be an individual, a household, or a country (Gillingham & Sweeney, 2012). Costs associated with new technologies are often high, because these technologies are still in a relative early-stage of development. Learning-by-doing and economies of scale have shown to decrease the costs (Gillingham & Sweeney, 2012; IEA, 2000; Jacobsson & Johnson, 2000; McDonald & Schrattenholzer, 2001). For instance, costs of wind power and photovoltaics worldwide have decreased substantially in the last decade. In countries such as Denmark, Germany and the Netherlands, governmental support was available to project developers. This support, in addition to Chinese subsidies for PV manufacturers, helped scale up the implementation of renewable energy technologies. Indeed, both in Germany and the Netherlands, bids for zero-subsidy offshore wind parks have been placed (to be delivered in 2024 and 2025 in Germany and in 2022 in the Netherlands) – a situation that seemed impossible only a few years ago[1] (Welisch & Poudineh, 2019).

Uncertainties resulting from unfamiliarity with technologies, as well as the absence of large-scale tests, create a second barrier to the implementation of novel technologies (Gillingham & Sweeney, 2012). When technologies are implemented on a larger scale, experience and know-how increase and uncertainties become fewer. In other words, the more mature a technology, the less uncertainties. Consequently, mature technologies are more likely accessible than immature technologies.

Thus, technology (in)accessibility is determined by two main indicators: technology maturity and costs. Both these indicators can be broken down into several sub-indicators: market penetration in the host country; market penetration in the wider region (neighbouring countries); market penetration in the country where the technology is most developed (best practice); upfront costs; and total costs (Figure 2). In the following sections, I discuss these sub-indicators in more detail

[1] It must be noted, however, that hidden subsidies are not taken into account. These include for instance the costs related to grid connection.

4.2 Technology maturity

The first indicator I selected to determine technology accessibility is technology maturity. The most widely accepted definition of technology maturity are the Technology Readiness Levels (TRL) developed by the National Aeronautics and Space Administration in the 1970s. Since then, numerous organisations have included TRL in their assessment of new technologies (Mankins, 2009). For instance, the European Commission uses the TRL to assess proposals under its Horizon 2020 research programme (Table 3) (De Rose et al., 2017).

Table 3. TRL Horizon 2020 (De Rose et al., 2017)

Levels	Characteristics
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in relevant environment
TRL 6	Technology demonstrated in relevant environment
TRL 7	System prototype demonstration in operational environment
TRL 8	System complete and qualified
TRL 9	Actual system proven in operational environment

While helpful when comparing the maturity of different technologies, the TRL do no help determine whether or not a technology is mature for the purpose of this thesis. It is highly unlikely purchasing countries would use Article 6 to invest in a technology that is anything less than TLR 9, because less mature technologies potentially do not reduce the amount of GHG emissions that the purchasing country anticipated.

To assess technology maturity in the context of inaccessibility, Rogers' (1971) concept of 'technology diffusion' is more helpful. Rogers defined diffusion of a technology as the process by which "an innovation is communicated through certain channels over time among members of a social system." According to Rogers' theory, the diffusion of a technology follows an S-curve (Figure 6). In the first phase, the technology is picked up by a small group of innovators (2.5%). Second, during the take-off phase, a group of early adaptors (13.5%) picks up the technology. The early adaptors are followed by the early majority (34%) and the late majority (34%). Finally, the laggards (16%) pick up the technology.

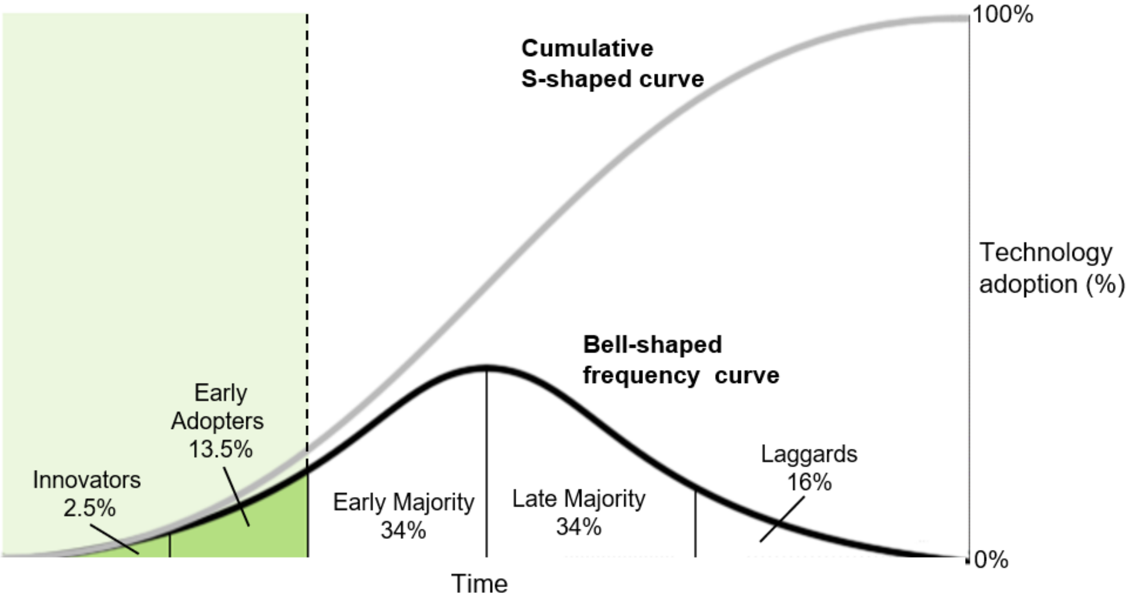

Figure 6. S-curve and bell curve (NewClimate Institute, 2018).

Policies and subsidies may help increase the market penetration rates of new technologies (Farmer et al., 2019), but at some point technologies no longer need financial support to increase their market penetration rates. For instance, the market growth of wind power and photovoltaics in Germany was stimulated by governmental support and accordingly higher than in countries were such support was absent (Lund, 2006). Indeed, in 2024 and 2025 zero-subsidy offshore wind parks are scheduled to be opened in Germany (Welisch & Poudineh, 2019). Article 6 should only be used to support technologies that are still in the innovation and take-off stages to help these technologies gain critical mass.

In my thesis, I looked at market penetration rates in the host country, in the region (i.e. neighbouring countries) and in the country were the technology is most developed (best practice). Market penetration rates in the host country give an indication whether technicians with the skills and know-how to install and maintain the technology are present and whether the infrastructure is already developed to some extent. Market penetration rates in the region provides information on the extent to which the technology is used in neighbouring countries that likely have similar socio-economic and geographical characteristics. Finally, market penetration rates in the country where the technology is best developed help determine whether the technology is completely novel (low market penetration rates in all countries) or already tested and in use (medium to high penetration rates in the country where the technology is best developed). In the latter case, risks associated with implementing a novel technology are fewer than if the technology immature in all countries.

4.3 Costs

The costs of a technology decrease as experience with (and diffusion of) that technology increases (Figure 7). As costs decline, the technology becomes more attractive to larger segments in the market. Support in the development stage could help gain critical mass and bring a technology to a 'tipping point', from which point onwards the technology is self-sustainable and does not require further support. Such support would also make low- and zero-carbon technologies competitive on a market dominated by fossil-fuel technologies that benefit from economies of scale, long periods of technological learning and socio-institutional embedding. As a result, consumers and firms alike prefer these technologies to expensive and unknown low- and zero-carbon technologies (Negro, Alkemade, & Hekkert, 2012).

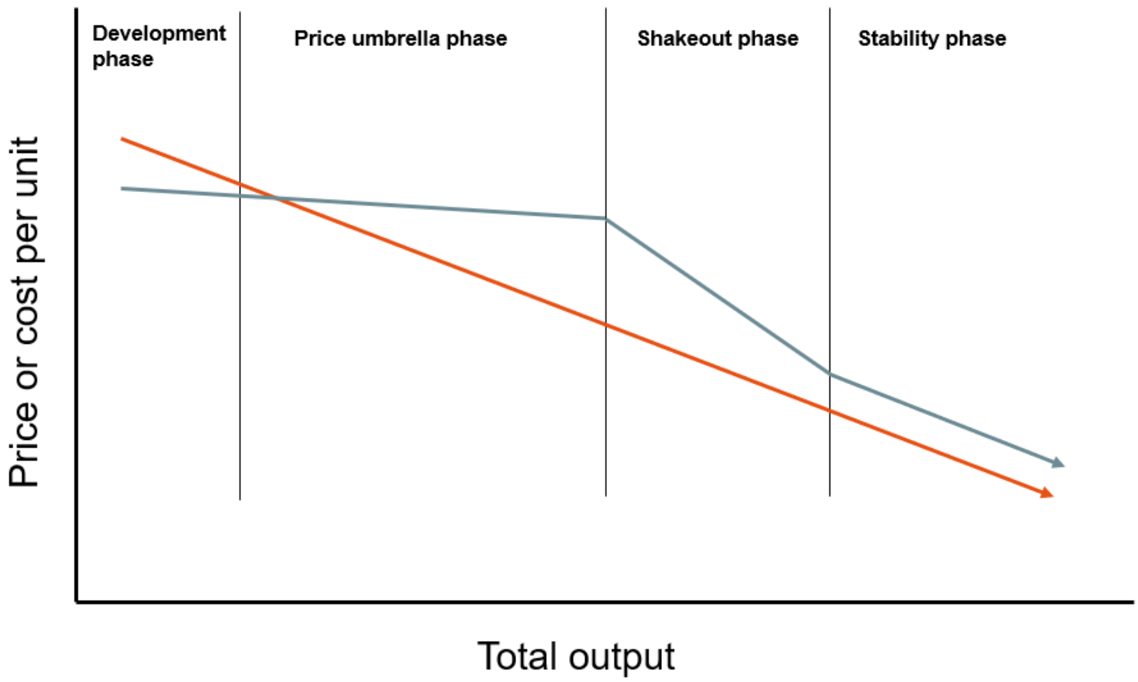

Figure 7. Price-cost relationship new products (adapted from IEA, 2000)

Thus, the costs associated with the technology in question are the second indicator for inaccessibility. The term 'costs' can be understood in various manners, including upfront costs, lifecycle costs and costs per tonne of CO_2 reduction. In this thesis, I assessed costs in two different ways. First, I looked at upfront costs of the technology compared to costs of the technology that is currently used. Second, I assessed total costs (upfront costs as well as operation and maintenance costs) of the potential technology, also compared to the technology that is currently used.

As explained in Chapter 2, I compared the costs of proposed technologies to the costs of the technologies they would replace. In the following three Sections, I outline why I selected 'upfront costs' and 'total costs' but not 'marginal abatement costs' as sub-indicators.

4.3.1 Upfront costs

High upfront costs may constitute a barrier to the uptake of a certain technology, even when overall costs are relatively low (e.g. Luthra *et al.*, 2015). Generally, new technologies have a higher risk of premature failure than conventional technologies, so there is a greater financial risk for the investor (Jaccard, Nyboer, Bataille, & Sadownik, 2003). Moreover, future benefits of novel technologies are less certain, which also contributes to making high upfront costs an important barrier to the adoption of new technologies (Bauner & Crago, 2015). Finally, project developers and host countries may not have the required financial resources for high upfront costs available. This is likely especially the case for the least developed countries and SIDS.

4.3.2 Total costs

In addition to upfront costs, total costs of a project also pose a barrier when they outweigh benefits. In such situations, projects would need targeted support to be profitable or cost-competitive (Lilliestam, Bielicki, & Patt, 2012). However, costs decrease as deployment increases, so likely only the first few generations need this support (Lilliestam et al., 2012).

Total costs include upfront costs and operation and maintenance costs. To compare lifetime costs of different technologies that each have different lifetimes, the levelised costs of energy (LCOE) is commonly used, which divides lifetime costs by lifetime energy production. Similarly, levelised cost of heat (LCOH) is a measure used to compare the costs of different heating systems (Equation 3). The LCOE and LCOH reflect the price at which the energy or heat must be sold to break even over the lifetime of the technology (Darling, You, Veselka, & Velosa, 2011).

$$\text{LCOH} = \frac{INV_t + \Sigma(\,FIXOM_t + VAROM_t + FUEL_t + DECOMM_t) * (1+r)^{-t}}{\Sigma_t HEAT_t * (1+r)^{-t}} \qquad \text{(Equation 3)}$$

Where INV_t represents the investment costs; $FIXOM_t$ the fixed operation and maintenance costs in year t; $VAROM_t$ the variable operation and maintenance costs in year t; $FUEL_t$ the fuel costs in year t; $DECOMM_t$ represent the decommissioning costs; $HEAT_t$ the generated heat in year t; and r the discount rate (Nian et al., 2016).

4.3.3 Marginal abatement costs

Marginal abatement costs (MACs) are an estimate of the cost associated with the last unit (i.e. the marginal cost) of emission abatement per tonne of CO2 reduction for a given technology (Kesicki & Strachan, 2011). MAC values are mostly estimated by models, which then simulate the cost of abatement across a specific sector or economy-wide (Isacs et al., 2016). A MAC curve combines the MAC values for different technologies. There are two ways to derive such a curve. First, the abatement costs and reduction potential of each technology can be assessed in isolation. Subsequently, different technologies are ranked based on their costs, from cheapest to most expensive. Second, it is possible to let an energy model perform many runs with different CO2 tax levels and to record the corresponding CO2 emissions reduction (Kesicki & Ekins, 2012; Kesicki & Strachan, 2011). Whereas MAC curves that are generated using the former technology depict each technology's abatement potential, an energy model provides aggregate abatement potential.

MAC curves are used by many countries worldwide to depict the costs and benefits of GHG mitigation actions, including the United Kingdom, Ireland, Mexico and the United States, and also by supranational bodies as the European Union, World Bank and the International Maritime Organization (Kesicki & Strachan, 2011). Indeed, MAC curves provide a good indication of which technologies can be implemented at negative or low cost. As such, when assessing and developing climate policies, countries could make use of MAC curves to get a good indication of what technologies to invest in.

Nonetheless, while MAC curves provide information about the costs associated with different GHG abatement technologies, they are not well suited for the purposes of this thesis. First, while various MAC curves are available, they are often relatively old (>10 years). This is a problem, because costs of various technologies (most notably solar PV) have dropped substantially in recent years. Also, more modern technologies are not included in MAC curves, but these technologies are less likely to be accessible than older technologies.

Second, MAC curves are usually country-specific, but do not exist for all countries around the world. Using the MAC curve that was developed to assess abatement technologies in the UK is unlikely to provide accurate information for reduction technologies in Mongolia, because of different market and climate conditions, which influence technologies' effectiveness and costs. Similarly, global MAC curves are unlikely to give accurate information on technologies' costs at a domestic level.

Third, while GHG abatement potential is an important consideration for host countries, it does not determine whether or not a certain technology is accessible. In theory, a very polluting technology could be inaccessible – other requirements in Article 6 would prevent that technology from being financed using Article 6.

In conclusion, (host) countries could use MAC curves in their policy considerations whenever such curves are available or can be generated. This likely helps countries reach the highest possible emission reductions against the lowest possible costs. Especially technologies with a negative abatement cost (i.e. implementing these technologies would save costs) should be adopted as soon as possible. However, for the three reasons mentioned above, my thesis, does not take marginal abatement costs into account when determining whether or technologies are accessible, but looks at upfront costs and total costs of the new technology compared to the costs associated with the existing technology.

4.4 Factors excluded from the assessment

4.4.1 Co-benefits

Technologies that reduce GHG emissions are likely to have many effects not directly related to GHG emissions, including on water resources, biodiversity, human health, employment patterns and agricultural yields (Nemet et al., 2010). Including these co-benefits in the cost assessment of technologies and recognising their economic value makes sense – especially from a climate and social perspective. However, calculating the range and full value of co-benefits is a difficult and time-consuming task that comes with challenges related to different time and spatial scales and to risk characterisations (Nemet et al., 2010). For my thesis, assessing and valuing all co-benefits related to NZEBs in Colombia and ground source heat pumps in Mongolia was not feasible. Indeed, calculating the whole range of co-benefits associated with a certain technology is likely not feasible for many Article 6 assessments. Moreover, co-benefits are bestowed upon society as a whole, not on the project developer or the government, so only a share of the co-benefits can be used by the government to finance new technologies. For this reason, co-benefits were excluded from the methodology. However, to show what the influence of co-benefits can be, I did two cost analyses in the case study on GSHPs in Mongolia: one time I excluded health-related benefits of reduced air pollution and the second time I included these benefits.

4.4.2 Risk profile

A second indicator not indicated in the accessibility evaluation methodology is the host country's risk profile. Research shows that political uncertainties related to for instance internal and external conflict, law and order, governmental stability and bureaucratic quality adversely influence foreign investment flows (Busse & Hefeker, 2007; Hayakawa, Kimura, & Lee, 2013). When faced with political risks, investors tend to increase the risk premium of investment projects, which leads to an increase in the cost of capital and consequently to a decrease in overall investment (Busse & Hefeker, 2007). Hence, political uncertainties decrease foreign investment finance and therefore hamper the implementation of GHG-emission-reduction technologies in countries. However, this barrier is not directly included my methodology to assess accessibility, because bad governance and political mismanagement should not be an excuse to show less ambition in decreasing GHG emissions. Moreover, political barriers like corruption and bureaucratic quality could compromise environmental integrity of Article 6 projects, as well as obligations related to for example human rights. Nevertheless, a country's risk profile influences discount rates of government bonds, so indirectly countries' risk profile is taken into account.

4.4.3 Policies hindering the uptake of new technologies

Governmental policies such as quotas, import tariffs and feed-in tariffs can hinder the uptake and diffusion of renewable energy technologies (Marques, Fuinhas, & Pires Manso, 2010). Further, limited availability and knowledge about new technologies, lack of competition, undefined property rights, public regulations and insufficient information also hinder the implementation of new technologies (Verbruggen et al., 2010). Governments can address many of these barriers, for instance by providing investors with sufficient information, removing fossil fuel subsidies and changing import tariffs. For this reason, I excluded policies that hamper the uptake of new technologies from my inaccessibility assessment. However, when countries consider engaging in Article 6 activities, they should assess the influence of domestic policies on the implementation of new technologies. Indeed, regulatory rules, including renewable portfolio standards and subsidies, can boost the implementation of expensive low-carbon technologies (Gillingham & Sweeney, 2012). Likewise, by removing subsidies and taxes that create a perverse incentive for firms to invest in fossil fuels, countries can encourage the implementation of low-carbon alternatives.

5 Net-Zero Energy Buildings in Colombia

In this case study I assessed whether NZEB apartments stratum 3 households[2] in Cartagena, a city on the northern coast of Colombia, would be classified as 'inaccessible' using the methodology that I developed.

NZEBs have a very low energy demand, which is met by renewable energy generated either on-site (e.g. PV panels) or close by (e.g. a wind power plant that provides a larger region with energy) (Marszal *et al.*, 2011). During a certain time period, usually a year, an NZEB has a net zero energy balance (Good, Andresen and Hestnes, 2015). To reduce energy demand as much as possible, NZEBs are well insulated and have advanced heating, ventilation and air conditioning systems.

5.1 Development status Colombia

Colombia is an upper middle-income country (World Bank, 2018) with a GNI per capita of 5,890 USD in 2017 (World Bank, 2019). I assume upper-middle income countries have budget available for additional climate measures, so I set the cost threshold at which NZEBs become too expensive for the Colombian government at 400% of the costs of a standard apartment building (see Table 1).

5.2 Technology maturity NZEB

NZEBs have not yet been built in Colombia (Fonseca, Jayathissa, & Schlueter, 2015), so the market penetration rate domestically is 0%. In the wider region, NZEB also hardly exist with only one known example of a holiday home in Panama (Hoque & Iqbal, 2015), so market penetration rates regionally are also 0%. Globally, NZEBs are most mature in the European Union, where from December 2020 onwards all new residential buildings must be nearly zero energy buildings (Council directive 2010/31/EU, Article 9). Within the EU, the Netherlands is the frontrunner in NZEB social housing projects (rented housing).[3] Indeed, the Dutch market for NZEBs has grown exponentially in the last decade, with only 90 new NZEBs built in 2013 and an expected 3656 in 2019 (Bekkema & Opstelten, 2019). In 2018, NZEBs constituted 2.7% of the total amount of newly built houses; in 2019 this percentage is expected to increase with 2.6 percentage points to 5.3% (Table 4).

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[2] In Colombia, household are divided in six strata, based on housing prices. Stratum 1 has the lowest housing prices and stratum 6 the highest.

[3] The NZEB refurbishment programme *Energiesprong* started in the Netherlands as government-funded innovation programme. See: https://energiesprong.org/ (Retrieved 3 June 2019).

Table 4. NZEB market penetration rates.

	Market penetration rates NZEB	Source/Comments
Colombia	0%	Fonseca, Jayathissa and Schlueter (2015)
Latin America (regionally)	0%	Hoque and Iqbal (2015)
Netherlands (best practice)	5.3% in 2019 (expected)	Own calculations

5.3 Costs of NZEBs

Net-zero energy buildings are not a widespread concept, with most existing NZEBs located in Europe and the United States. Of these NZEB projects, apartment buildings constitute 11% (Y. Lu, Wang, & Shan, 2015). No published examples of NZEBs exists for in Central and Latin America, other than a holiday house in Panama (Hoque & Iqbal, 2015) and a proposal for a school in Barranquilla, Colombia (Fonseca et al., 2015). Accordingly, there was no data from Latin America available to perform a cost assessment. For this reason, I assessed the costs of four different NZEB components: triple glazing, wall insulation, a solar PV system and induction stoves.

5.3.1 Glazing (single glazing versus triple glazing)

According to Piderit *et al.* (2019), who defined a framework for a energy standard for NZEBs in Chile, the lack of industrial-manufacturing infrastructure that allows domestic firms to produce NZEB equipment such as heat pumps and PV panels, forms one of the main obstacles to NZEBs in Chile. Colombia faces the same challenge and would need to import many capital goods for the construction of a net-zero energy building.

To reduce thermal load of buildings in tropical climates as much as possible, incoming solar radiation must be reduced to a minimum and buildings must be well insulated to keep cool air in and warm air outside (Halawa et al., 2018). Simple measures, such as façade orientation, external shell colour and shading can considerably reduce a building's energy demand for cooling. In Cartagena, for instance, the façade orientation should be in the north-south direction, so the building is protected from the sun (Osma Pinto, Sarmiento Nova, Barbosa Calderón, & Ordóñez Plata, 2015). In the absence of data on the investment costs of the building envelope, I assumed that the costs of simple and inexpensive measures like façade direction and shading are negligible and that the costs of the building envelope are equal for a standard building and an NZEB. Further, I assumed that the measures to increase insulation lead to a difference in costs between standard buildings and NZEB: different glazing types (Table 5) and wall insulation (Table 6). As Gentle, Aguilar and Smith (2011) and Lucero-Álvarez, Rodríguez-Muñoz and Martín-Domínguez (2016) showed, roofs with high R-values reduce day-time heat gains, but also reduce night-time heat losses. Thus, in areas with tropical climates, like Cartagena, well-insulated roofs are counterproductive and insulating only the building's walls is the best option (Lucero-Álvarez et al., 2016).

Table 5. Costs of single and triple glazing (based on prices in the Netherlands, in the absence of price estimations in Colombia).

	Single	Triple (HR+++)
Average price per m2 in USD[4]	20	105
Total costs for a building with 48 apartments in USD	12,500	66,500

Table 6. Costs of no insulation and wall insulation.

	No insulation	Wall insulation (polystyrene with a thickness of 100mm)
Price of insulating a single-family house in Mexico in USD[5]	0	3,600
Price of insulating a building with 48 apartments in USD[6]	0	65,000

5.3.2 Energy system (natural gas and electricity from the grid versus solar PV)

The second component of buildings is the energy system. Standard buildings in Colombia are connected to the natural gas grid and the electricity grid. In my analysis, I considered the tariffs that households in stratum 4 pay and assumed that these fully cover the costs associated with the production and transport of natural gas and electricity.

The Colombian government divided the population in six strata, based on housing prices. Strata 1 to 3 receive subsidised electricity, so they pay less than the market price per kWh. Strata 5 and 6 pay a contribution on top of the market price. Stratum 4 pays the market price and does not receive any subsidies (Li, Wang, & Yi, 2018). To determine current costs for electricity that household pay, I used

[4] In the absence of data for Colombia, I took prices for glass in the Netherlands as an indicator and converted the costs to Colombian pesos.
[5] The house's size is 6x8x3m (Lucero-Álvarez et al., 2016)
[6] Based on the proposed project in Cartagena (https://www.phius.org/NAPHC2018/PHIUS2018%20Straus-Bueno_Final.pdf), I estimate the length and width of the building 25x17m and the height 18m (6 floors)

the electricity tariffs in Cartagena (the region Bolivar) for stratum 4, although the proposed project targets stratum 3. However, the tariffs for stratum 3 would need to be complemented by governmental subsidy and together these two would amount to the tariff for stratum 4. Electricity tariffs vary between regions, in Cartagena (department Bolivar), the energy tariff for stratum 4 amounted to 415 COP per kWh,[7] which equals 0.12 USD per kWh.

In April 2018 the average amount of electricity consumed by stratum 3 households was 283 kWh per month[8] or 3396 kWh per year. In addition, stratum 3 households in Cartagena use 18m^3 or 180 kWh natural gas per year[9]. Accordingly, a building with 48 households consumes 163,000 kWh electricity and 10,600m^3 gas per year (Table 7).

In Europe, NZEBs have on average a 90% lower energy demand than a standard building (BPIE, 2011). As Colombia has less stringent standards for standard buildings, energy demand of NZEBs in that country are very likely more than 90% lower than for standard buildings. However, to give a conservative estimate, I assumed the 90% energy demand reduction also applies to Colombia. Hence, the energy demand one building with 48 apartments amounts to 27,000 kWh. This energy is produced using solar PV. Operation and maintenance costs associated with solar PV arise from replacing inverters (normally every 15 years), occasional cleaning and electrical system repair (Branker, Pathak, & Pearce, 2011). The proposed project in Cartagena will not install hot water, so I did not consider costs that would be associated with for instance solar boilers.

Further, I assumed that NZEBs are connected to the electricity grid, so households can consume electricity from the grid at night and feed excess electricity into the grid. Another possibility would be to disconnect the buildings from the grid and install battery storage, which would increase NZEB costs. However, for sake of simplicity, I assumed a grid connection and that this connection comes at negligible costs. Moreover, I assumed the NZEB injects as much electricity into the grid as it consumes and that the price per kWh is equal for injected and consumed electricity.

Table 7. Energy demand in a standard apartment building and an NZEB apartment building.

	Standard building (48 apartments)	NZEB (48 apartments)
Annual electricity demand in kWh	163,000	27,000
Annual natural gas demand in m3	10,600	N/A

[7] Electricarbe. Retrieved from: www.electricaribe.co.
[8] Sistema Único de Información (2019). *Superintendencia de Servicios Públicos Domiciliarious.* Available at: www.sui.gov.co
[9] According to UPME (2017), households' energy demand is met by 55% electricity and 35% natural gas.

5.3.3 Appliances (gas stoves versus induction stoves)

The final component of the NZEB are the appliances. I assumed that all appliances are the same in a standard building as in an NZEB (e.g. washing machine), except for the stoves. A large majority of Colombian households in urbanised areas use natural gas for cooking (Osma Pinto et al., 2015), with 8.5 million subscribers across the different strata in 2016 (Promigas, 2017). However, by definition NZEBs cannot use natural gas for cooking or other purposes, so the NZEB project will need to replace the prevailing gas stoves by electric stoves – either conventional or induction.

Whereas induction stoves are becoming more and more popular in Europe and the United States, they are still uncommon in Latin America. However, induction stoves are highly efficient, compared to both gas stoves and traditional electric stoves (Smith & Sagar, 2014; Sweeney, Dols, Fortenbery, & Sharp, 2014), and can thus play an important role in decarbonisation of the housing sector. In addition to increased efficiency, induction stoves are also more user-friendly, because it is easier to control the heating temperature. Further, heat generation stops as soon as the pot is removed from the stove, so people cannot accidentally burn their hands when touching the stove surface (Banerjee, Prasad, Rehman, & Gill, 2016).

5.3.4 Overview costs of the different building components

Table 8 provides an overview of the upfront and total costs associated with a standard apartment building and a NZEB apartment building in Cartagena, Colombia. The upfront costs in a standard building arise from single glazing and gas stoves, whereas the upfront costs in an NZEB reflect the costs for triple glazing, wall insulation, installing solar PV and inverters and induction stoves. In a standard building, overall costs include the upfront costs, the replacement of the gas stoves every 17 years, as well as the costs of electricity and natural gas consumption. The total costs in the NZEB, expressed in Net Present Value (NPV) include the upfront costs, costs of replacing the inverters after 15, 30 and 45 years; the solar panels after 25 years; and the induction stoves after 17 and 34 years; as well as maintenance costs for the solar PV system (cleaning and occasional reparation). It is important to remember that these costs reflect not total costs of the whole building, because I excluded the major part of the building envelope from my calculations.

Real interest rates and government bond yields have been close to 5% in the past few years. Therefore, I did the cost assessment using discount rates of 5%, but also of 0% and 10% to see what difference this makes to the calculations' outcomes. As Table 8 shows, the higher the discount rate, the cheaper both the standard building and the NZEB get and the smaller the cost difference. However, the percentual difference between costs of a standard building and costs of an NZEB increases as the discount rate goes up. This is explained by the fact that a large share of the costs associated with NZEBs occur upfront (installation of solar PV, insulation, triple glazing), whereas the costs of a standard building are more evenly spread out over the building's lifetime (costs for natural gas and electricity demand).

Table 8. Costs of a standard building and an NZEB building with a lifetime of 50 years (costs exclude among others the largest part of the building envelope, these are assumed equal for both building types).

	Upfront costs in USD	Total costs at 0% discount rate (NPV in USD)	Total costs at 5% discount rate (NPV in USD)	Total costs at 10% discount rate (NPV in USD)
Standard building	20,000	2,100,000	620,000	295,000
NZEB	156.000	2,500,000	880,000	430,000
NZEB as % of the standard building	765%	115%	140%	145%
Actual difference between standard building and NZEB	136,000	400,000	260,000	135,000
Accessibility score	0	9.4	8.6	8.5

5.4 Accessibility score NZEB in Colombia

When calculating the accessibility score, I used the total costs with a 5% discount rate, because real interest rates and Colombian government bond yields have been around 5% in the past few years. Using the initial weight allocation of 25% for upfront costs, 25% for total costs, 20% for technology maturity of NZEBs in Colombia, 20% for technology maturity of NZEBS in Latin America and 10% for technology maturity of NZEBS in the Netherlands (best practice), the accessibility score of NZEBs is 2.8. As Table 9 shows, the accessibility score is 3.6 when costs are the most important indicator and 1.9 when technology maturity receives most weight in the calculation.

Arguably, 'technology maturity in the Netherlands' should receive a score of 10, because the technology is widely used and can therefore be seen as mature. This would result in an accessibility score of 4.1 in the scenario where costs and technology maturity are equally important, which is close to the score of 2.8.

Moreover, to assess the influence of the 400% threshold for costs, I also calculated the accessibility score using threshold of 600% and 200%. This resulted in accessibility scores of 3.0 and 2.1, in the initial scenario.

Based on these results, NZEBs are likely inaccessible to Colombia, mainly as a result of the high upfront costs. The sub-indicator 'total costs' scores an 8.6 and is unlikely a barrier to NZEBs. Further, technology maturity is very low in Latin America, but NZEBs are a well-developed concept in other parts of the world. As explained in Section 3.5, countries should seek financial sources as much as possible, because that means they can count the associated emission reductions toward their own NDC target. Since upfront costs of NZEBs seem to be the main barrier, but overall costs are not very high compared to a standard building's overall costs, Article 6 finance is likely not the best option for Colombia (see also Figure 5).

Table 9. Outcomes of the accessibility score of NZEBs with different weights attached to the indicators (using a discount rate of 5%)

	Score per sub-indicator	Weight (%), initial scenario	Weight (%), costs most important	Weight (%), technology maturity most important
Upfront costs	0	25	40	10
Total costs	8.6	25	40	10
Technology Maturity Colombia	0	20	8	30
Technology maturity regionally (Latin America)	0	20	8	30
Technology maturity best practice (Netherlands)	3.3	10	4	20
Accessibility score		2.8	3.6	1.9

6 Ground source heat pumps in Mongolia

The second case study concerns replacing existing coal power plant with heat pumps for residential buildings in Khovd city, located in western Mongolia. Two coal power plants supply most multi-unit buildings (residential, business and public) in the city with heat.

Mongolia is one of the most sparsely populated countries in the world and has an extreme climate, with long and cold winters. For this reason, adequate heating is vital to the country's population and demand is mostly met by coal, which accounts for 96% of the total fuel utilisation (Ministry of Environment and Tourism, 2018)

Mongolia's dependence on coal, however, leads to major air pollution in urban areas, with ambient annual average particulate matter (PM) concentrations in for instance Ulaanbaatar exceeding Mongolian air quality standards by 10-15 times (World Bank, 2011). Air pollution has significant health impacts on cities' populations and is associated with lung cancer and cardiorespiratory diseases (Arden Pope et al., 2002). In addition, coal-fired heat plants emit significant amounts of GHG emissions, contributing to global climate change. Thus, both from a climate and public health perspective, it is obvious that coal should be replaced by cleaner resources. While there is a huge potential for solar and wind power in Mongolia, the implementation of these technologies on a large scale is hampered by the challenge of storing electricity. Another potential solution for indoor temperature heating in Mongolia are ground source heat pumps, which could replace coal fired power plants and coal stoves.

Heat pumps use electricity to pump heat from low temperature heat sources (e.g. air, ground soil, underground water) to a higher temperature level that is useful for space heating and domestic hot water supply (Self, Reddy, & Rosen, 2013). Two major heat pump types exist: ground source heat pumps and air source heat pumps (Su, Madani, & Palm, 2018). The latter type does not perform adequately in extremely cold climates and are therefore unlikely a suitable option for Mongolia (Stryi-Hipp, 2016). GSHPs, however, have a larger potential in cold climates, although costs increase as outdoor temperatures decrease (Ozyurt & Ekinci, 2011; Self et al., 2013).

According to Soltani *et al.* (2019), comparative costs of geothermal heat compared to the prevailing energy sources may be a barrier in regions where cheap energy is available and the government has little incentive to decarbonise the energy system. Since Mongolia has abundant coal resources, it is likely that costs are a barrier to the instalment of GSHPs.

6.1 Development status Mongolia

According to the World Bank, Mongolia is a lower-level income country (World Bank, 2018). As such, Mongolia is unlikely to have considerable financial resources available to invest in GHG-emission-reduction technologies. I assumed the threshold at which technologies become too expensive for Mongolia at 200% the costs of coal-fired heat plants, which are currently used to provide residential apartments with heat (see Table 1 for an overview of income levels and corresponding thresholds). I also used thresholds of 150% and 300% to assess whether and to what extent these would change the accessibility score.

6.2 Technology maturity heat pumps

There are a few examples of GSHPs in Mongolia, for instance a public school in a peri-urban district of Ulaanbaatar (GGGI, 2018) and in hotels and kindergartens (Dorj, 2015). Most of the installed heat pumps serve as pilot projects. Although exact data on total installed capacity in Mongolia is unavailable, based on these few examples, I estimated market penetration to be 1%.

GSHPs have been widely used in China in the past decade (Yuan, Cao, Sun, Lei, & Yu, 2012), with the area using GSHPs expected to be 500 million m^2 in 2020 (Ma, Kim, & Hao, 2019), which is only a tiny fraction of the total floor area of 50 billion (Lixuan, Nan, David, Wei, & Khanna, 2014). In Russia, another neighboring country, various studies assessed the feasibility of GSHPs (e.g. Vasilyev *et al.*, 2016) but ground source heat pumps are not a commonly used technology. For this reason, I estimated market penetration to be less than 1% of overall building square meters in both China and Russia.

Although heat pumps are not widely used in east Asia and many other parts of the world, the technology in itself is well developed. In Sweden, heat pumps generate approximately 25% of heating and hot water (Swedish Energy Agency (Energimyndigheten), 2014). Data on the share of heat pumps in Swedish multi-family residential buildings is unavailable, but of the two million single-family houses, approximately 20% are heated with GSHPs (Gehlin & Andersson, 2016).

Using the market penetration rates of GSHP in Mongolia, Russia and China and Sweden, and attaching a weight of 40% to the first two rates and of 20% to market penetration in Sweden, the accessibility score for technology maturity is 2.5 (Table 10).

Table 10. Market penetration rates of GSHP in Mongolia, Russia and China and Sweden.

	Market penetration rates GSHP	Accessibility score	Source/Comments
Mongolia	<1%	0.625	Only few examples of GSHPs exist
Regional (Russia and China)	<1%	0.625	Only few examples of GSHPs exist
Best practice (Sweden)	20%	10	Gehlin and Andersson (2016)
Overall	-	2.5	40% weight attached to the penetration rates in Mongolia and Russia and China and 20% to the penetration rate in Sweden.

6.3 Costs of heat pumps

According to Nian *et al.* (2016), the lifetime of a coal-fired heat plant is twenty years. However, the older heat plant in Khovd has been in use since 1986, so in my calculation, I assumed a lifetime of 40 years. The upfront costs for a heat pump are 2100 USD per kW installed[10] (GGGI, 2018), whereas the upfront costs for a coal-fired heat plant are only 28 USD per kW (Nian et al., 2016).[11] Thus, the upfront costs per KW are 75 times as high for the heat pump as for the coal-fired power plant. However, because heat pumps are more efficient than the two existing heat plants, actual upfront costs are 10 times as high.[12]

Between 1998 and 2017, interest rates in Mongolia fell within 23.05% and 6.135%, with rates below 10% since 2007.[13] Rates on government bonds also fluctuate: between May 2013 and November 2014 yield ranged from 7.5% to 14.8% (Asian Development Bank, 2014). A currently outstanding bond has a coupon rate of 8.75%.[14] I used this percentage to calculate the total costs (expressed in LCOH) of coal-fired heat plants and heat pumps. In addition, I performed a sensitivity analysis using rates of 0%, 5% and 10% (Table 11).

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[10] The upfront costs consist of 1500 USD for borehole drilling and 600 USD purchasing costs.
[11] This number for the upfront costs was back-calculated from the total investment and heating capacity of an existing heating plant in Shandong province, China (personal correspondence with the author). Other estimations of the investment costs for coal-fired heat plants were not available.
[12] Installed capacity for heat pumps: 4478 kW and installed capacity for power plants: 32,598 kW.
[13] World Bank (2019). "Interest rate spread (lending rate minus deposit rate,%)". Available at: https://data.worldbank.org/indicator/FR.INR.LNDP?locations=MN&view=chart (Retrieved 3 June 2019).
[14] BondEvalue (2019). "Mongolia (Government)". Available at: https://bondevalue.com/bond-market/Government-USY6142NAA64 (Retrieved 3 June 2019).

Table 11. Overview of upfront and total costs for coal heat plants and heat pumps in Khovd, Mongolia.

	Upfront costs in USD for the capacity needed to meet heating demand	LCOH in USD per kWh with a discount rate of 0%	LCOH in USD per kWh with a discount rate of 5%	LCOH in USD per kWh with a discount rate of 8.75%	LCOH in USD per kWh with a discount rate of 10%
Coal-fired heat plant lifetime 40 years	912,000	0.0407	0.0330	0.0303	0.0299
GSHP lifetime 20 years	9,400,000	0.1115	0.1290	0.1452	0.1512
Costs GSHP compared to the coal-fired power plant	1,000%	275%	390%	480%	505%
Accessibility score costs	0	0	0	0	0

Both the upfront costs and the total costs (measured in LCOH) of heat pumps are considerably higher than the upfront and total costs of coal-fired heat plants, with upfront costs of heat pumps 10 times as high as those of the heat plant and the LCOH 5 times as high with a discount rate of 8.75%. Accordingly, using Equation 2 and the outcomes for a discount rate of 8.75%, the sub-indicators 'upfront costs' and 'total costs' both receive a score of 0.

$$X_{i(nom)} = 10 - (10 \cdot \frac{(X_i - X_e)}{(X_t - X_e)}) \qquad \text{(Equation 2)}$$

$X_{i(nom)} = 10 - (10 \cdot \frac{(480-100)}{(200-100)})$ = -28 (truncated to 0)

As can be concluded from the cost difference between GSHPs and heat plants, using a cost threshold of 300% would not change this score. A cost threshold of 150% would result in an accessibility score of 1.3 when the discount rate is 0%, but scores or the other discount rates would remain 0. The score of 1.3 would also clearly indicate 'inaccessibility'.

6.4 Accessibility score heat pumps in Mongolia

Using the initial weight allocation of 25% for upfront costs, 25% for total costs, 20% for technology maturity of heat pumps in Mongolia, 20% for technology maturity of heat pumps in the region and 10% for technology maturity of heat pumps in Sweden (best practice), the accessibility score of heat pumps is 1.3. As Table 12 shows, the accessibility score becomes very low (0.5) when costs are the most important indicator and a bit higher (2.4) when technology maturity receives most weight in the calculation. However, in all three scenarios, the accessibility score is relatively low and indicates that heat pumps are likely not accessible for Mongolia.

Since both costs and technology maturity of heat pumps are likely a barrier to the uptake of GSHPs, Mongolia could consider using Article 6 of the Paris Agreement to finance heat pumps in Khovd (or elsewhere in the country).

Table 12. Outcomes of the accessibility score of heat pumps with different weights attached to the indicators (using the outcomes for a discount rate of 8.75%).

	Score per sub-indicator	Weight (%), initial scenario	Weight (%), costs most important	Weight (%), technology maturity most important
Upfront costs	0	25	40	10
Total costs	0	25	40	10
Technology maturity Mongolia	0.625	20	8	30
Technology maturity regionally	0.625	20	8	30
Technology maturity Sweden	10	10	4	20
Accessibility score		**1.3**	**0.5**	**2.4**

6.5 Taking co-benefits into account

As explained in Section 4.4.1, the methodology that I developed to assess technology accessibility omits co-benefits. Identifying the full range of co-benefits and expressing them in monetary value is often difficult. Nonetheless, co-benefits should play an important role in environmental decision-making, because these are benefits to the public and have a certain value. To see what the effect of considering the co-benefits of improved air pollution would be on the cost of installing heat pumps, I estimated the value of public health co-benefits per tonne of CO_2 and included this value in the calculation of the LCOH of heat pumps.

In 2016, a study estimated total deaths as a result from air pollution in Mongolia in 2013 to amount to 2,400, resulting in a total welfare loss of 2 million USD (The World Bank and Institute for Health Metrics and Evalution, 2016). Similarly, a World Bank (2011) report estimated that PM levels in Ulaanbaatar amounting to annual health costs of 175-725 million USD. Although Khovd city is much smaller than

Ulaanbaatar (approximately 30,000 inhabitants compared to 1.5 million), its geographic and climate situation is comparable, making these numbers a fair indication of the magnitude of air pollution impacts.

Table 13 provides an overview of the estimated public health co-benefits associated with CO_2 emissions. Nemet, Holloway and Meier (2010) reviewed various studies and found a mean co-benefit value of 81 USD per tonne of CO_2 in developing countries.[15] In another study, West *et al.* (2013) estimated that co-benefits per tonne of CO_2 reduction amount to 50-380 USD for the global average, 30-600 USD for the United States and western Europe; 70-840 USD for China; and 20-400 USD for India in 2030.[16] Co-benefits in India are relatively low due to an assumed shift to biomass combustion and local $PM_{2.5}$ increase as a result of changing monsoon patterns (West et al., 2013).

Moreover, co-benefits change between regions and over time because they are estimated using the Value of a Statistical Life (VSL), which is based on GDP. Accordingly, it places a higher value on human life in industrialised countries than in developing countries. Also, co-benefits are estimated to increase in developing countries where increased urbanisation and industrialisation is expected. While the approach of VSL brings moral dilemmas, it is widely used in literature, allowing researchers assessing climate policy and health costs (Markandya et al., 2018).

Table 13. Overview of public health co-benefits provided by various studies.

Study	Country or region	Co-benefits in US$ per tonne of CO_2
Nemet, Holloway and Meier (2010)	China	81
West *et al.* (2013)	China	70-840
West *et al.* (2013)	India	20-400
West *et al.* (2013)	United States and western Europe	30-600

[15] Most studies reviewed by Nemet et al. (2010) did not provide monetary values, so the average of US$ 81 is based on two studies in China.
[16] The authors calculated co-benefits using low and high values of statistical life, which resulted in a range in which co-benefits are expected to fall.

Recent studies indicate that the health benefits of climate policy outweigh the mitigation costs (Markandya et al., 2018; West et al., 2013). This is likely to be true for Mongolia, which suffers from extreme air pollution, but also uses inexpensive coal and old coal-fired power plants.

According to data from (GGGI & Government of Mongolia, 2016b), the two heat plants in Khovd emit 19,000 tCO_2 annually.[17] About 38% the total building volume connected to the heating district are residential buildings. Assuming these buildings also consume 38% of the total heat, an annual reduction of 7277 tCO_2 can achieved by installing heat pumps in Khovd. Taking a conservative estimate (70 USD) of the health benefits associated with each tonne of CO_2 reduction, co-benefits in Khovd would amount to 0.5 million USD annually. A high estimate of 800 USD per tonne of CO_2 would lead to yearly benefits of 5.8 million USD in Khovd.

Table 14. Overview of LCOH of heat pumps considering co-benefits, compared to the LCOH of heat plants (USD per kWh). A lifetime of 40 years for the heat plants and 20 years for the heat pumps and a discount rate of 8.75% were assumed.

	No co-benefits	**Co-benefits 70 US per tCO_2**	**Co-benefits of 235 USD per tCO_2**	**Co-benefits of 400 USD per tCO_2**	**Co-benefits of 800 USD per tCO_2**
LCOH heat pump in USD per kWh	0.1771	0.1107	0.0318	-0.0516	-0.2485
LCOH heat plant in USD per kWh	0.0318	0.0318	0.0318	0.0318	0.0318

As Table 14 shows, co-benefits substantially reduce the LCOH of the heat pumps in Khovd. If co-benefits amount to 235 USD per tonne of CO_2, heat pumps are competitive with power plants. Moreover, with a benefit of 400-800 USD per tonne of CO_2, heat pumps are not only cheaper than the existing heat plants, their LCOH is even negative, so Mongolia can save money by replacing the heat plants in Khovd with heat pumps for residential buildings.

This analysis shows that considering co-benefits in a cost assessment can considerably change the costs associated with a certain technology. It is important to note, however, that the costs and benefits of the heat pumps would be borne by a project developer, whereas society as a whole profits from the associated health benefits. Nevertheless, the Mongolian Government is likely to spend less on health

[17] According to the GGGI (2016) report, the two power plants emit 19150kgCO2 annually on a production of kWh. According to these numbers, emissions of the power plants are 0.5g per kWh, which means the two power plants are extremely efficient. Since this is not the case, I assume the $kgCO_2$ in the report is a mistake and should be tCO_2.

costs and receive more taxes, as people can be employed for a longer part of their life. Accordingly, Mongolia could use part of the co-benefits to subsidise heat pumps in Khovd.

7 Discussion of results

In my thesis, I developed a methodology that can be used to determine whether or not technologies are accessible to certain countries. Article 6 of the Paris Agreement recognises cooperative approaches in order to allow for *higher ambition* (Article 6.1, emphasis added). Higher ambition likely implies that countries can only sell emission-reduction units that they would not have achieved without international support. Thus, only technologies that are otherwise inaccessible to host countries should receive finance under Article 6. In my thesis, I assessed technologies' accessibility by considering both technology maturity and costs. In this Chapter I discuss the difficulties I encountered, their impact on my results and how I addressed them.

7.1 Threshold for costs

I had to answer the question at what point costs, both upfront and overall, become too high for a country. I assumed that countries with a higher GDP have more budget available to spend on new technologies than countries with a lower GDP and used the World Bank income classification to assign different thresholds to different income groups, where the thresholds for the high-income countries is high and for the low-income countries low. These thresholds measure costs in relative terms (i.e. the relative difference between the new technology and the technology that is currently used in the host country) and not in absolute numbers. The problematic aspect of this approach is that the actual difference between an existing and new technology is more likely to determine whether or the new technology is accessible. For instance, 5,000 USD is 500% of 1,000 USD and 5,000,0000 USD is 500% of 1,000,000 USD, but a country is more likely able to finance 4,000 USD extra than 4,000,000 USD. However, setting a threshold based on absolute cost increases requires detailed information on the host country's budget, public spending etc. Within this thesis' scope, collecting, analysing and interpreting this information is too time-consuming. The approach that I took made it possible to set thresholds for different country groups and gives a good indication of whether costs are too high for a host country, especially because the methodology was used to assess medium-scale projects, where the costs range from ten thousands to millions.

7.2 Indicators' weight

The weight that I attached to the (sub-)indicators is, although based on expert judgment, arbitrary. To assess the influence of the weight, I performed a sensitivity analysis which showed that NZEBs in Colombia and GSHPs in Mongolia are inaccessible in three scenarios: one where costs and technology maturity are equally important, one where costs count for 80% and finally one where technology maturity counts for 80%. Thus, although the indicators' weight influences the outcome, changing the weights does not lead to different conclusions

7.3 Influence of domestic policies on accessibility

Although import tariffs, taxes and subsidies, can considerably alter the cost-competitiveness of technologies, my methodology to assess accessibility does not consider such policies, with the exception of the electricity subsidy for stratum 3 households in Colombia. If I had included these policies in my methodology, however I would have needed to assess their influence on local employment, domestic manufacturers etc. For instance, solar panels could be cheaper in a certain country if the import tariff on foreign PV panels would be removed. However, the purpose of this tariff might be to protect the local PV manufacturers and removing it could result in people losing their jobs, which may or may not outweigh the lower costs of PV panel. Doing a cost-benefit assessment of domestic policies is a tedious task that requires very detailed information. Project developers and potential host countries are unlikely to have all this information at hand, or the required time to perform a thorough cost-benefit assessment of domestic policies. Therefore, I decided to exclude domestic policies in my accessibility assessment. Nevertheless, as discussed in Section 4.4.3, I recommend countries to assess whether or not the uptake of clean, low-carbon technologies is hindered by policies.

7.4 Threshold for technology maturity

Based on Rogers' Theory of Diffusion (Rogers, 1971), I set the threshold for technology maturity at 16% market penetration (from that point, technologies generally do not need further support). Newly built NZEB houses in the Netherlands make up only 2-5% of the total newly built houses, which according to my own threshold, indicates the technology is far from mature. However, looking at the exponential increase of new Dutch NZEB houses in the past five years and considering that many different housing corporations are building NZEB houses throughout the country, I would argue NZEB is mature in the Netherlands. Thus, the 16% market penetration threshold is possibly too high for this specific case study and should be lowered. However, when I assessed the influence of the 16% threshold on the outcome of NZEBs in Colombia and assigned a score of 10 to the indicator technology maturity in the Netherlands, this resulted in an accessibility score of 4.1, compared to 2.8 in the initial scenario. A 4.1 also indicates inaccessibility and the difference between the two scores is small enough to justify using the 16% threshold in this case study. Moreover, the 16% threshold is the best available measure of 'technology maturity' and likely to give adequate results, including in my two case studies.

7.5 Lack of data

Since only one example of a realised NZEB in Latin America exists, data on the costs of NZEBs on that continent was not available. For this reason, I assessed only the costs of glazing (single versus triple), wall insulation (versus no insulation), energy demand (natural gas and electricity from the grid versus solar PV) and stoves (gas stoves versus induction stoves). In the absence of Colombian data, I used Dutch and global prices to approximate the costs of glazing and solar PV, respectively. Costs are likely higher in Colombia than the global average, because triple glazing and solar PV components must be imported. Therefore, I used conservative costs estimates, which allowed me to use the Dutch and global data for the case study in Colombia. Further, I used data from a Mexican case study to estimate the costs associated with insulating the NZEB apartment building in Cartagena. Colombia and Mexico are located in the same region, have comparable climates and a comparable development status, so the Mexican cost data likely applies to Colombia too. As I show in Section 7.7 below, my cost assessment is comparable with Sartori, Noris and Henkel's (2015) conclusions on NZEBs' costs in Europe, so the costs approximations for NZEBs in Colombia can be considered correct.

7.6 Co-benefits

I excluded co-benefits from the cost assessment in the methodology, because it is difficult to determine the full spectrum of social and environmental externalities that are associated with a certain technology and to attach monetary value to them. Further, co-benefits are not bestowed upon the project developer, who would normally bear the costs, or the government, but rather upon society as a whole. Accordingly, it is not possible to use the full value of co-benefits for new technologies. For this reason, I excluded co-benefits from my methodology. Nonetheless, as shown in the Mongolian case study, co-benefits can substantially change the outcome of a cost assessment. In some cases, this could lead to the conclusion that technologies are inaccessible, when they probably are accessible. Governments are very likely to profit from a share of the co-benefits and can utilise the money to subsidise technologies. In Mongolia, for instance, GSHPs would improve air quality, so less people would develop respiratory diseases and public health would improve. Moreover, the government would receive more taxes, because people live longer and healthier lives and are thus productive for a longer time period. Thus, some of the co-benefits are bestowed upon the Mongolian government, which could use these benefits to subsidise GSHPs. Accordingly, I recommend future studies to identify and include the main co-benefits in the cost assessment whenever possible to get a sense of the potential additional resources that are available to finance a new technology.

7.7 Comparison with other studies

The idea of using Article 6 support for 'inaccessible technologies' is novel and has not yet been discussed in academic literature. Accordingly, comparing this thesis' methodology and results to other studies was not possible. However, I was able to compare my costs assessments with other studies.

According to Sartori, Noris and Henkel (2015), a number of selected NZEBs in Europe have investment costs that are 9-27% higher than the investment costs of standard buildings, with larger differences in countries that have less strict building standards. Although Colombia has an energy efficiency plan in place, government effectiveness and regulatory quality is not high (Zabaloy, Recalde, & Guzowski, 2019), so the cost difference between NZEBs and standard buildings in Colombia is likely to be higher than in Europe. Moreover, in the absence of a regional market for NZEB components, these components must be imported at high costs (Piderit et al., 2019). Further, in my cost assessment I considered four different components and not the whole building. The investment costs of these four components in an NZEB are more than 600% as expensive as the standard components. I assume other building components are equally expensive for NZEBs and standard buildings. If these components would also be included in the analysis, which was not possible due to a lack of data, the actual difference between NZEBs and standard buildings would remain the same as in my assessment, but the relative difference would diminish. This would bring my outcome closer to the range indicated by Sartori, Noris and Henkel (2015).

Dalla Rosa and Christensen (2011) found that the LCOH of GSHP in terraced and detached houses in Denmark ranged between 0.15 and 0.24 EUR per kWh, which is 0.17-0.27 USD per kWh, with a lifetime of 30 years and a discount rate of 6%. This is slightly higher than the LCOH I calculated (0.1452

USD per kWh) but the electricity costs are lower in Mongolia (0.07 USD per kWh) (GGGI, 2018) than in Denmark[18] because Mongolia generates its electricity using old power plants and cheap coal. Further, labour in Mongolia (National Statistics Office of Mongolia, 2017) is considerably cheaper than in Denmark[19]. Further, Lu *et al.* (2017) found that the upfront costs of a 10kW GSHP are around 31,000 AUD or 22,000 USD. This is close to the instalment costs of 2.100 USD per kW that I used in my analysis.

Further, according to Nian *et al.* (2016), the LCOH of a coal-fired heat plant in Shangdong Province, China, are 0.0180 USD per kWh with a discount rate of 10%, a lifetime of 20 years and a boiler efficiency of 90%. The LCOH that I calculated is slightly higher, 0.0303 USD per kWh with a discount rate of 8.75% and 0.0299 USD per kWh with a discount rate of 10%. This price difference could be attributed to the large difference in boiler efficiency. The boilers in Khovd's power plants are only 60% (GGGI & Government of Mongolia, 2016a), so coal consumption is much higher in Khovd than in Shangdon and fuel costs therefore likely higher.

The LCOHs that I calculated fall within the same range as the LCOH for heat pumps as found by Dalla Rosa and Christensen and the LCOH for heat plants as found by Nian et al. This enforces the conclusion that my calculations are likely correct.

[18] According to Statistics Denmark, the electricity price for households was 2.3297 DKK per kWh, which is approximately 0.35USD kWh. Retrieved from: https://www.statbank.dk/statbank5a/default.asp?w=1920.
[19] The average annual wage in Denmark was 320,040 DKK, which is about 49,000 USD. Retrieved from: https://www.statbank.dk/statbank5a/selectvarval/saveselections.asp.

8 Conclusion

In this thesis I answered the following four research questions:

1) What does the Paris Agreement provide with regard to emission trading and how does this differ from provisions under the Kyoto Protocol?
2) In addition to Article 6 of the Paris Agreement, what other finance sources are available to countries that want to acquire inaccessible technologies and when should countries opt for what finance source?
3) What could be a methodology to identify ‘inaccessible technologies’?
4) How would net-zero energy buildings (NZEB) in Colombia and ground source heat pumps (GSHP) in Mongolia be classified when applying this methodology?

The Paris Agreement allows Parties to trade emission-reduction units to increase ambition in their mitigation actions. Unlike its predecessor, the Paris Agreement requires all countries to set ambitious emission-reduction targets in their NDCs. Further, the 1.5 ºC limit requires net-zero emissions by 2050, which means that all countries and sectors must decarbonise in the next three decades. As a result, the scope for either selling or purchasing emission-reduction units is very limited. Host countries need reduction units to reach their domestic NDC target and potential purchasing countries should reduce domestic emissions to reach net-zero emissions by 2050. For these reasons, Article 6 of the Paris Agreement should only be used to finance ‘inaccessible technologies’. However, ‘inaccessible technologies’ should not be financed by Article 6 activities per se, because other finance sources exist. These include for instance loans and grants from multilateral development banks or the Green Climate Fund. When countries finance ‘inaccessible technologies’ with alternative finance sources, the associated emission-reduction units can be counted towards their own NDC target. For this reason, alternative finance sources are preferable from both the host country and climate perspective. Therefore, countries should only opt for Article 6 when other options are not available.

To identify ‘inaccessible technologies’ that could receive Article 6 support, I developed an evaluation methodology that considers technology maturity and its costs. I assessed ‘technology maturity’ by looking at market penetration rates of the technology in the host country, in the region (neighbouring countries) and in the country where the technology is most developed. Further, I divided ‘costs’ in ‘upfront costs and ‘total costs’. Based on these indicators, technologies receive an accessibility score between 0 and 10, where 0 indicates the technology is likely inaccessible to the host country and a 10 that the technology is likely accessible.

Using this methodology, I assessed two technologies: NZEBs in Colombia and GSHPs in Mongolia. NZEBs in Colombia received a score of 2.8 when a discount rate of 5% and a timeframe of 50 years were assumed and when the indicators ‘technology maturity’ and ‘costs’ were given equal weight. To assess the influence of indicators’ weight on the final outcome, I performed a sensitivity analysis. When ‘costs’ are the most important indicator (80% weight), the accessibility score increased to 3.6. Further, when ‘technology maturity’ is considered most important, the accessibility score decreased to 1.9. Important to note is that the sub-indicator ‘upfront costs’ received a score of 0 and ‘total costs’ a score of 8.6. This indicates that upfront costs, rather than total costs are a barrier to the implementation of NZEBs in Colombia. Further, with almost no existing NZEB projects in Latin America, market penetration rates in both Colombia and the region are very low, which is also likely to pose a barrier. Since the difference in total costs between a standard building and an NZEB is relatively low, climate finance other than Article 6 is most likely the best option for Colombia (see Figure 5). Indeed, if Colombia uses alternative finance sources, the country could count the emission-reduction units associated with NZEB projects towards its own NDC target.

In the second case study I assessed how accessible GSHPs are for Mongolia. Using the methodology that I developed, ground source heat pumps would receive an accessibility score of 13, assuming a discount rate of 8.75% and a 20-year lifespan. This score indicates that the technology is very likely inaccessible, caused by high upfront and total costs and by low market penetration rates in Mongolia and regionally. Hence, if Mongolia were to install heat pumps, it would need financial and technical support. Due to the high overall costs and low technology maturity regionally and domestically, Article 6 is an interesting option for Mongolia and could be used to finance heat pumps in Khovd.

The method that I developed in this research project could be used to assess the accessibility of NZEBs and heat pumps in other countries than Colombia and Mongolia, as well as the accessibility of other technologies. Such analysis can help guide countries in determining whether or not foreign support for the instalment of certain technologies is necessary. Moreover, it can help determine which factors are likely to pose a barrier to the implementation of technologies and, accordingly, which financial sources are most suited to overcome these barriers. A major obstacle would be the absence of country-specific data on technologies' costs, which is a problem inherent to the assessment of novel technologies. This obstacle can be overcome by approximating costs using data from other countries or regions, preferably from countries with similar geographic and human development characteristics. However, in cases where potential host countries or project developers use proxies, results should be interpreted carefully.

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