



Review

Barriers to investment in utility-scale variable renewable electricity (VRE) generation projects

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ABSTRACT

To effectively mitigate climate change, variable renewable electricity (VRE) is expected to substitute a great share of current fossil-fired electricity generation. However, VRE investments can be obstructed by many barriers, endangering the amount of investments needed in order to be consistent with the Paris 2 °C target. To help policy-makers better understand and assess these barriers, an integrated framework was developed. It establishes a clear connection between barriers identified in literature and the investment decision-making process, based on the project life of VRE assets. Barriers in this framework are defined as factors hindering the realization of a positive final investment decision (FID), which can lead to investment withdrawal.

Based on this research, we argue that addressing so-called “symptomatic” barriers alone is hardly effective when the “fundamental” barriers remain untouched. It also demonstrates that monetary and fiscal policies can have side-effects on VRE investments. We suggest that a comprehensive policy framework to support VRE should not be solely limited to the narrow context of climate and energy policy, and the electricity market. It should be incorporated in a broader context including monetary and fiscal policies. When re-designing these macroeconomic policies, their potential negative impacts on VRE investments should be considered.

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1. Introduction

To effectively mitigate the worst impacts of climate change, the Paris Agreement agrees to limit the increase in global average temperature to 2 °C above pre-industrial level and seeks to further limit the temperature increase to 1.5 °C [1]. This requires a significant contribution of renewables in the global electricity generation portfolio to decarbonize the power sector [2]. In particular, variable renewable electricity (VRE), which is electricity converted from stochastic energy flows (e.g. wind and solar), is expected to play an indispensable role in substituting electricity generation from fossil fuels. The 2 °C scenario of the International Energy Agency (IEA) indicates that the combined penetration of wind and solar in global electricity supply has to increase from 4% to 25% between 2013 and 2040 [3]. In some regions like the European Union (EU), this figure may be as high as 37% by 2040 [3]. Hence, a sustainable and robust growth of investments in VRE is needed for the foreseeable future.

Driven by climate policies (including renewable energy support) and increasing cost reduction associated with technological learning and economies of scale, a strong growth trend for global VRE investments has been witnessed since 2000 [4,5]. During 2004–2015, annual investment in new VRE assets increased from 38.1 billion USD₂₀₁₅ to 270.6 billion USD₂₀₁₅,¹ resulting in an increase of total installed VRE capacity by a factor of 13 (from 51 GW to 669 GW) [5,6]. It is estimated that a cumulative investment in VRE amounting to 4444 billion USD₂₀₁₅ between 2016 and 2035 is the minimum level needed to be consistent with the 2 °C climate target [5,7]. However, concerns still exist to whether sufficient VRE investments can be realized. Investment in power generation assets, in general, feature sunk capital costs and uncertainty surrounding future returns and costs [8]. VRE investments, as a result of their specific techno-economic characteristics, can be distinguished from investments in conventional fossil-fired power plants in two main aspects. Firstly, because VRE projects tend to have a higher capital-intensity (measured by capital expenditures (CAPEX)'s share in total operating expenditures (OPEX) and CAPEX) than fossil-fired plants, they are more exposed to capital constraints and the cost of capital (WACC) [9–13]. Secondly, featuring variable, uncertain and location-dependent outputs, VRE projects are more exposed to downside revenue risks (i.e. actual revenue received below the expected revenue) [14,15]. Not only facing these two inherent disadvantages, VRE investments can be obstructed by many other barriers. They either reduce the economic appeal of the investment project, or hinder the process of accomplishing necessary steps before final investment decisions (FID) can be made [2]. These barriers have been discussed in a wide range of literature, but in a fragmented manner. They tend to focus on only one type of barrier to VRE investments or limit the scope of their discussion from a single perspective. For instance, Hirth et al. [15] and Munoz and Bunn [16] respectively demonstrate that the current EU

electricity market design may be detrimental to the business case of VRE investments from the revenue perspective and the risk-return perspective. From the cognitive and institutional perspective, Masini and Menichetti [17] show that biased perceptions and preconceptions defer the decision-making process for VRE investments, favoring the existing energy production model based on fossil fuels. Drawing from a case study, Jami and Walsh [18] conclude that the lack of public participation may contribute to the rejection of VRE investments. It seems that based on the current knowledge of literature, a comprehensive overview is missing that connects different barriers and their underlying contributors. This adds difficulty to diagnose and address these barriers. This paper aims to deliver a literature review-based analysis that can provide such overview, through developing an integrated framework to analyze barriers to VRE investments as identified from literature. In such framework, we define barriers to VRE investments as factors hindering reaching a positive FID, which can end up with investment withdrawal. Hence, a clear link can be established between barriers and the decision-making process for VRE investments. This serves as the basis to identify and analyze barriers. The scientific contribution of this paper lies in two main aspects. Firstly, the existing body of both empirical and theoretical literature is limited when pertaining to investment decision-making in power plants and renewable energy, e.g. Wustenhagen and Menichetti [19]; Groot et al. [4]. Often, these literature sources tend to be detached from the project life of VRE assets. Complementing existing literature, this paper bridges the project life and the investment decision-making process. Thus, it offers deep insights for different stakeholders and the scientific community on how VRE investment decisions are made in practice and what factors affect the decision-making process. Secondly, findings of this paper can feed into the discussion of how barriers to VRE investments can be effectively tackled. This helps to safeguard necessary VRE investments consistent with the 2 °C climate target.

This paper is organized as follows: In Section 2 an integrated framework is developed to represent the decision-making process for investments in VRE assets from a project developer's perspective, given its essential role in making a FID. This is performed through connecting the investment decision-making process with the project life of VRE assets. Section 3 applies the integrated framework to analyze and combine key barriers to VRE investments identified from existing literature, based on the division of the decision-making process into several stages. The survey of relevant literature is based on a few targeted keywords, such as “investment decision-making”, “renewable energy” and “barrier”. A snowball method is also used to facilitate the literature survey process. This allows the identification of other literature sources from the reference list of a surveyed paper and the identification of new papers citing the surveyed paper. To include literature from different fields that are related to VRE investments, we do not take a specific view to select and assess literature, i.e. an explorative approach is adopted. A total number of 144 literature sources are reviewed (see Table 1), which consist of peer-reviewed journal

¹ Original data are given in nominal value. Deflators (http://stats.areppim.com/calc/calc_usdlrxdeflator.php) are used to obtain their constant USD₂₀₁₅ value.

Table 1
Summary of reviewed literature sources.

Academic literature sources	Peer-reviewed journal papers	63
	Textbooks, professional books, PhD theses, conference/working/discussion papers published by academic organizations	29
Non-academic literature sources	Government documents (e.g. European Commission, OECD) and reports published by organizations affiliated to the government (e.g. IEA, 23 IEA-Renewable Energy Technology Development, World Bank)	23
	Government-funded project reports	10
	Consultancy/think-tank/association reports and column articles (e.g. Bloomberg New Energy Finance)	19
Total		144

papers (63), other academic literature sources (29) and non-academic literature sources (52).² In section 4, a synthesis of the review-based analysis is given, including policy implications drawn for policy-makers. We point out the recommendations for further research in section 5.

2. Development of the integrated framework

The development of the integrated framework for the research was mainly drawn from literature that describes the project life of a VRE asset. The project life of a VRE asset typically consists of several project steps that follow a temporal sequence. They are pre-feasibility study and site prospecting, VRE resource assessment, environmental impact assessment (EIA) and permits acquisition (e.g. land, building, grid connection), off-take arrangement and support scheme application, capital access, engineering and equipment procurement and contracting, construction and commissioning, commercial operation and maintenance, and decommissioning³ [20–23]. Since the step of engineering and equipment procurement and contracting and the step of construction and commissioning involve the commitment of the majority of costs throughout the project life, the implementation of these two project steps marks the actual start of the investment. This implies final investment decision (FID) must be made prior to these two steps [23]. Investments will only be committed once the FID is made. Therefore, using the FID as a demarcation, the project steps before FID comprise the investment decision-making process. Each project step naturally formulates a decision-making step. Empirically, the decision-making process serves to confirm that the investment case considered is a good investment for the project developer, i.e. with a satisfying economic outcome under a sufficiently high confidence interval [19]. To streamline the decision-making process, the recognized decision-making steps were further grouped into two sequential principal stages before the decision outcome of the FID: stage prior to capital access (i.e. project development stage) and capital access stage.

VRE investments are subject to many unknown events affecting capital and time expenditures associated with each project step and future cash flows of the investment project. To inform successful decision-making, project developers should be able to evaluate the viability of the project under these unknowns. Based on the measurability of knowledge, Zeckhauser [26]; Diebold et al. [24]; Stirling [25] distinguish these unknowns into three states:

risks/known unknowns (with specified outcomes and probabilities), uncertainties/unknown unknowns (with specified outcomes and unspecified probabilities) and ignorance/unknowable unknowns (with unspecifiable outcomes and probabilities). Although it is uncertainties and ignorance that are mostly encountered in VRE investments, it is common practice to treat uncertainties as risks via assigning a (subjectively) estimated probability distribution function and be wary about ignorance [24,28,29]. Hence, in this paper the term “risk” is used to generalize the three states of unknowns, and it is specified to downside risk. In traditional finance theory, the assumption of perfect information and full-rationality implies that investment decision-making should be informed by the statistically measurable risk [30–32]. However, behavioral and psychological literature points out the subjective perception of risk in reality, reflecting bounded rationality, can strongly affect investment decisions, depending on the developer's judgment and attitude towards risks [4,17,31]. Furthermore, due to high unknown and unknowable risk level associated with complex VRE investments, their actual risk is *a priori* hardly measurable. Consequently, risk has to be treated with a high degree of subjectivity, which is subject to different psychological, behavioral and institutional attributes [31]. To take these into account, we deem it useful to add “preliminary risk scanning” as an additional stage, to the very beginning of the decision-making process. This enables to capture the process of moving the project from investment intention (or formulation of the investment intention) to development action.

Fig. 1 presents the developed integrated framework for the VRE investment decision-making process, which consists of three main stages. We will elaborate on these three stages below and how they move forward towards reaching the FID.

• Stage 1: Preliminary risk scanning

Before deciding whether to start the development of a potential VRE project, the project developer is expected to preliminarily scan⁴ the risk profile of the project. If risks are perceived too high for the developer to accept or handle, the project will be rejected [17].

• Stage 2: Project development

This stage concerns establishing the layout of the project and thoroughly assessing the economic feasibility of the investment [23]. It consists of four sequential project steps. Although not comparable to the upfront capital costs required to start the investment, each step of the project development still involves sizable investment and time. Therefore, the project developer must decide whether to move the project forward at the beginning of

² To better capture first-hand and up-to-date information, a number of non-academic literature sources (52 in total) are also used. Many of them are widely-cited, and they come from official government documents, well-acknowledged organizations and other primary sources (e.g. IEA, World Bank, Bloomberg New Energy Finance). Peer-reviewed reports (e.g. IEA-RETD) are also included among them.

³ Depending on projects and countries, the sequence of project steps may be slightly different. For instance, VRE resource assessment can be performed earlier than site selection and prospecting, and off-take arrangement can be earlier than permits acquisition. Note that some project steps can also be implemented in parallel [20].

⁴ Note that preliminary suggests that more comprehensive risk assessment need to be conducted to support later stages of investment decision-making. They are incorporated in the iterative process of economic appraisal paralleled to the project development stage in this integrated framework.

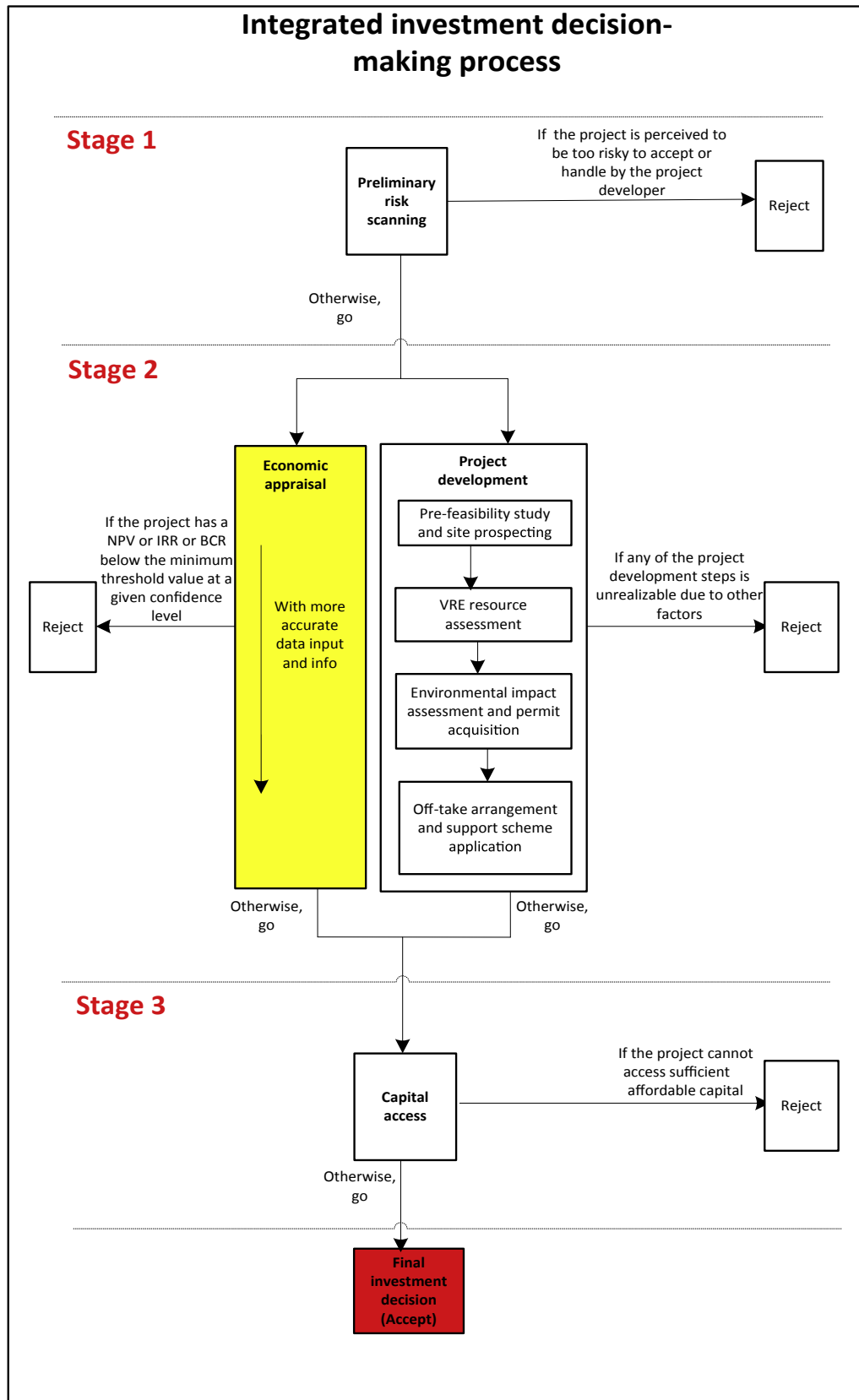


Fig. 1. Integrated framework for VRE investment decision-making process.

each step. The decision-making process is assisted by an iterative process of economic appraisal for the investment project in parallel to the project development [33]. The investment decision would be rejected if any step of the project development is unrealizable, either due to an undesirable result of the economic appraisal or other factors (e.g. unaffordable costs or complex administrative procedures associated with a step). This minimizes potential losses.

This iterative process also improves the quality of the economic appraisal and reduces its unknown level. This is because as more steps of the project development are proceeded, more accurate data and information inputs regarding the future cash flows of the project will be disclosed [19,33]. Consequently, the unknown state of project risks tends to switch from unknown unknowns to known unknowns. However, the unknowns of risks do not necessarily decrease. To thoroughly take project risks into account, the iterative economic appraisal can be based on a probabilistic discounted cash flow (DCF) approach. Key performance indicators (KPI) of this approach can be based on either net present value (NPV), internal rate of return (IRR), benefit-cost ratio (BCR),⁵ or discounted payback period (DPBP). KPI selection depends on the preference of the project developer, but in principle a minimum required rate of return (i.e. financial hurdle rate) in the form of discount rate should be met [19]. In the early steps of the financial appraisal, a higher risk-adjusted discount rate can be used to estimate the expected value of these KPI, reflecting the state of high unknown unknowns. In the late steps with more data available, Monte Carlo simulation or statistical mean-variance analysis can be used to give the cumulative probability distribution of the KPI [34]. The resulting at-risk value of KPI (value at a given percentile or minimum value at a given confidence level) can effectively inform the developer whether to proceed with the next project step [35]. The corresponding minimum criterion⁶ is that the NPV-at-risk value should be above 0, the IRR-at-risk value should be above the discount rate, the BCR-at-risk should be above 1, and the DPBP-at-risk value should be below the lifetime of the project. Otherwise, the project would be rejected due to the lack of economic appeal.

• Stage 3: Capital access

After passing through the project development stage and the iterative process of economic appraisal, the decision-making process would enter the capital access stage. Final investment decision would only be accepted if the project developer is able to access sufficient affordable capital to finance the investment. Otherwise, the project would be rejected. Once the final investment decision is accepted, the project developer can start the investment.

3. Review-based analysis of barriers to VRE investments

The integrated framework provides a basis to identify and analyze barriers to VRE investments from the reviewed literature. It enables to connect barriers with different investment decision-making stages, where barriers increase the likelihood of the investment project being rejected. Barriers for each decision-making stage and their attributes are analyzed in the following sections.

⁵ BCR is the ratio between the present value of the future cash flows and the upfront capital costs. Sometimes it is also referred to as profitability index (PI).

⁶ Threshold values for different KPI under the minimum criteria are consistent, which reflect the situation of the required rate of return being just met. Note that it is possible that firms or project developers may set additional cut-off criterion for one or more KPI beyond the minimum criterion, which to some extent reflect their bounded-rationality.

3.1. Barriers at preliminary risk scanning stage

Barriers at this stage mainly increase the project developer's risk perception towards the VRE investment project, which can lead to rejection of the investment. Risk perception is a joint function of both risk judgement and risk attitude [36]. The former represents the cognitive/mental process of defining the risk levels of the project, while the latter reflects the affective/emotional attitude towards the judged risk [37,38]. Three types of risk attitude can be distinguished: risk-seeking, risk-neutral and risk-averse. If the project developer is risk-averse, the impact of risk judgment can be amplified and it leads to a higher risk perception [37]. Therefore, risk perception increases either through increased risk judgement or increased risk averseness.

Risk perception can be influenced by actual risk factors for VRE investments, which can occur at different steps of the project life [31]. De Jager and Rathmann [39], Oxera [40], Hampl and Wustenhagen [31], Waissbein et al. [10] have provided different but similar classifications for these actual risk factors. They include policy risk, public acceptance risk, technology risk, permit risk, construction risk and electricity market risk, to name a few. Most of them will be treated as barriers in later sections of this paper. Here we focus on psychological, behavioral and institutional attributes that can give rise to additional risk perception, which constitute barriers to VRE investments [41]. These attributes include **path dependence, the lack of knowledge and experience, the lack of confidence, the lack of sustainable strategic value, and individualistic worldview and culture.**

3.1.1. Path dependence

Path dependence suggests past investments in fossil-fired plants can impact today's decision-making for investment in VRE projects [4]. It has implications for VRE investments at energy system and firm level, both of which can increase the risk perception for potential VRE project developers. At a system level, historical development of fossil-fired plants and complementary infrastructure has displayed multiple comparative disadvantages for VRE technologies [42]. In particular, increasing the uptake of VRE requires large-scale development of flexibility resources, e.g. grid infrastructure, demand response, storage and flexible fossil-fired plants. The lack of flexibility in the current energy system may lead to technological lock-in and increased risk perception for VRE investors. At a firm level, risk perception towards VRE investments of incumbent firms that were heavily involved in fossil fuel investments may be affected by their historical activities [4]. This seems particularly true for large utilities that own large fossil-fired plants and associated infrastructure [43]. Even when government tightens the environmental standard, these utilities tend to retrofit and upgrade existing plants instead of switching to VRE technologies, to avoid the write-off large sunk costs [43].

3.1.2. Lack of confidence

The lack of confidence and misinformation about VRE can increase the risk perception towards VRE investment [44]. Masini and Menichetti [17] distinguish two types of confidence related to VRE investments: technology confidence and policy confidence. Technology confidence reflects the project developer's personal belief about the technological performance of VRE. Compared with fossil-fired electricity generation, VRE technologies are less established and often perceived as less mature [17]. Skepticism about the reliability and adequacy of VRE technologies increase the risk perception of project developers [43]. This is often exacerbated by misinformation about VRE technologies created by the fossil fuel lobby [45,46]. Policy confidence reflects the developer's personal belief in the effectiveness of policy that aims to stimulate and

streamline VRE development [17]. The lack of long-term credibility, stability and visibility in policy can reduce such policy confidence.

3.1.3. Lack of knowledge and experience

The lack of knowledge regarding VRE technology and its operation can increase the perceived risk towards VRE investment, because the perceived unknown level increases in absence of sufficient knowledge [17,44]. Consequently, even risk-seeking investors may feel unable to hedge against VRE technology risk [17]. If the knowledge gap fits the developer's personal biases towards VRE technology, it may further reduce the confidence level in VRE investment [17].

Experience enables a better estimate and management of the actual risk level. Through learning by doing, experience in early adoption of VRE technology creates knowledge, which indirectly affects risk perception [44]. It also directly reduces the perceived risk due to increased familiarity with the technology. Based on an empirical survey of European investors, Masini and Menichetti [17] point out that investors with greater experience in the renewable energy sector tend to favor renewable energy technology over fossil-fired technology. This suggests that lack of experience may increase the risk perception towards VRE investment.

3.1.4. Lack of sustainable strategic value

Firms with a stronger sustainable strategic value tend to be more accepting and hold a less risk-averse attitude towards VRE investments [19,47]. A large government ownership often increases the sustainable value and financial robustness of firms, reducing the risk perception [19]. For instance, in Germany municipal utilities tend to weigh environmental motives higher than commercial utilities in investment decision-making [43,48]. This suggests that the lack of sustainable strategic value constitutes a barrier to VRE investments.

3.1.5. Individualistic worldview and culture

Risk perception for VRE investment can be affected by the worldview and culture of investors. Chassot et al. [141] prove that investors holding an individualistic worldview favoring a free-market tend to affectively amplify their risk perception towards VRE investments under high regulatory exposure than other investors. Similarly, Weber and Hsee [37] show that, due to social diversification, investors from a collectivist culture (e.g. China) tends to hold a lower risk perception than their peers from an individualistic culture (e.g. United States, Germany) for the same investment option. Therefore, an individualistic worldview and/or culture can hinder VRE investments.

3.2. Barriers in an iterative economic appraisal process

In this paper, the (expected) NPV of the VRE project and its at-risk value using the probabilistic discounted cash flow approach are adopted to perform the economic appraisal process. Therefore, barriers are here defined as attributes that reduce the absolute NPV of VRE investments or its relative value to fossil-fired plants. Attributes increasing the variance of NPV can also be deemed as barriers to VRE investment, which tend to reduce the NPV-at-risk value.⁷ Fig. 2 shows an illustrative example of the probability density function for NPV and the NPV-at-risk value at 5 percentile (or 95% confidence level). The NPV-at-risk value here represents

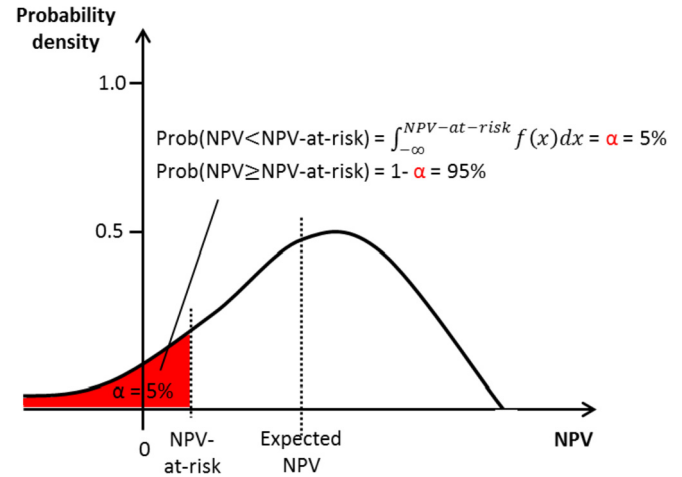


Fig. 2. Probability density function of NPV and NPV-at-risk at 5 percentile. Source: adapted from Ye and Tiong [35].

the minimum NPV value with 95% probability. It can be generated through a Monte Carlo simulation, which draws repeated random samples of input parameters for the NPV calculation and statistically analyzes the calculation result. This requires defining the probability distribution for each input parameter and their correlations.

The NPV can be calculated via the following formula:

$$NPV = -I + \sum_{i=1}^L \frac{(B_i - C_i)}{(1 + r)^{-L}} \quad (1)$$

where:

- I: Upfront capital costs;
- B_i : Annual revenue;
- C_i : Annual operating & maintenance costs and tax payments;
- r: Discount rate;
- L: Project economic lifetime

Formula (1) shows that barriers can result in a lower NPV or NPV-at-risk value through negatively influencing any of the input parameters of the calculation. In other words, barriers can influence either the expectancy of the economic lifetime, upfront capital costs, discount rate, annual tax payments or annual revenue of the VRE investment.

3.2.1. Underestimation of project economic lifetime

Underestimating project economic lifetimes tends to result in underestimated project NPV. Branker et al. [49] report that although the manufacturers' guaranteed lifetime for solar PV system is usually 20–25 years, working lifetime well beyond 25 years is increasingly shown in practice. Once the guaranteed lifetime has passed, the system would still generate electricity at negligible cost. Therefore, a more credible value on the economic lifetime should be provided by industries that fully considers the trade-off between the actual working lifetime and the system degradation rate [49]. If the guaranteed lifetime is used to determine the project NPV, it can give rise to misconception.

3.2.2. High unit upfront capital costs and capital-intensity

Despite the ongoing effects of technological learning and economies of scale, to date the upfront capital costs per unit of installed capacity for VRE world-wide are generally still higher than

⁷ Under a higher variance, the probability distribution function for NPV becomes wider. Thus, the NPV-at-risk value at a given percentile tends to decrease. Note that a lower expected NPV also reduces the NPV-at-risk value, because it shifts the entire probability density function leftwards.

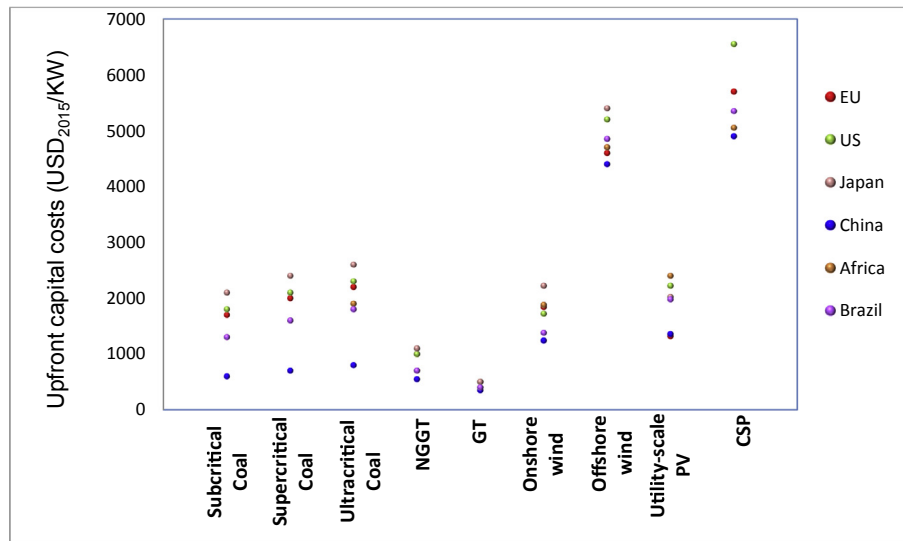


Fig. 3. Unit upfront capital costs for investments in different fossil-fired electricity and VRE generation technologies. Source: Data derived from IEA [142].

that of gas-fired power generation (see Fig. 3). In terms of firm capacity,⁸ unit upfront capital costs are even more expensive due to the variable nature of VRE. The unit upfront capital costs of onshore wind and PV have experienced significant cost reduction in past years, while a reversed trend has been observed for offshore wind since 2000 [50,51]. Half of the increased costs can be explained by increased depth and distance to shore and increased commodity price, while the rest can be largely ascribed to increased offshore turbine price due to limited competition between manufacturers [52]. Quality control for locational-specific mega-turbines, increased construction costs associated with disjointed turbine design and construction, the lack of standardization and fragmented construction industries may also limit the cost reduction for offshore wind [51].

VRE investments also face higher capital-intensity than fossil-fired electricity generations [53–55]. For instance, the capital-intensity for gas-fired generation and coal-fired generation is typically 0.4 and 0.45, while it is 0.8 for onshore wind and even higher for solar [56]. This tends to negatively impact the NPV of VRE investments, as more costs are paid upfront rather than being discounted in the future.

3.2.3. Non-accelerated tax depreciation policies

Tax depreciation policies affect the distribution of annual tax payment of VRE assets. A higher depreciation rate enables the project to claim higher after-tax net revenue in its early operating lifetime, which increases the NPV. This is in the case of accelerated depreciation that prescribes a depreciation time shorter than the project lifetime [57]. On the contrary, non-accelerated depreciation policies (e.g. straight-line depreciation) decrease the economic appeal of VRE.

3.2.4. Expected revenue insufficiency

Expectancy of insufficient annual revenue reduces the absolute NPV of VRE investments and its relative value to fossil-fired electricity generation. At worst, the project will be rejected if it fails to break even, i.e. $NPV < 0$. Since the revenue received by VRE is the

sum of the market revenue of selling electricity, the revenue of auxiliary products and subsidies from support policy schemes, fundamental causes for revenue insufficiency are related to unfavorable electricity market conditions or unfavorable policies:

- Unfavorable electricity market conditions

The market revenue of VRE is contingent on conditions of the electricity market. In a liberalized electricity sector, the revenue from electricity sales in the spot market usually constitutes the largest source of market revenue, depending on the electricity spot price and sales volume. A **very low regulatory price-cap** can decrease the spot price [58]. Frew et al. [59] also report that the **spot price is often depressed by overcapacity** due to the disconnection between the spot market and administratively-determined higher reliability standards. This gives rise to a market failure [60,61]. Exacerbated by the large increase in VRE capacity but the limited market exit of surplus baseload capacity and the post-recession low demand, severe overcapacity has been identified in various regions, e.g. Germany and Australia [143,62,63]. This decreases revenue for all generators including VRE. VRE may, however, be more sensitive to a lower spot price compared to other generators. The short-run marginal cost (SRMC)-based price settlement in the spot market seems to not favor VRE characterized by close-to-zero SRMC. Firstly, due to the so-called “**merit-order effect**”, there is a tendency of spot price decrease when VRE generation replaces the marginal thermal plant used to set the price [64]. Secondly, with increased VRE penetration, the spot price during periods of VRE generation tends to be further reduced because of the “**decreased temporal correlation effect**” between VRE and demand [15]. These two effects have already been demonstrated by many empirical and model-based studies [16,144]. **Decreased electricity sales volume** of VRE also causes market revenue reduction. It occurs during curtailment resulting from **limited flexibility** of the power system to absorb surplus VRE generation [14]. System inflexibility can also be amplified by the overcapacity of baseload plants, since it increases the must-run generation level.

Besides providing electricity products, VRE is also able to provide balancing capacity products in the balancing market [65,66]. In particular, the downward balancing services provided by VRE are cost-effective because no opportunity cost is involved [66]. However, **biased market conditions** in terms of low time resolution and

⁸ Firm capacity represents the percentage of the nominal capacity of a power plant that can be served as guaranteed power supply with a certain level of system reliability [139].

early gate closure time create an entry barrier for VRE to provide reliable balancing services [66]. This reduces potential revenue streams for VRE. Similarly, an unfavorable imbalance settlement system for allocating system balancing costs can reduce VRE's revenue. For instance, a two-price system penalizes any imbalance of electricity delivery from schedule, even if such imbalance counteracts the system imbalance [67]. This punishes VRE more often due to the difficulty in forecasting [68]. It also discriminates against smaller market participants, which often include VRE, since large market participants are more capable of netting their imbalances [69].

- Unfavorable policies

Relying on market revenue alone, currently it seems less likely for VRE to recover its high upfront capital costs [140]. This can be largely explained by unfavorable Energy & Climate policies that **fail to create a level playing field** for VRE to compete with fossil-fired electricity generation in the market. Firstly, due to the **incomplete internalization of negative externalities** (e.g. climate change, air pollution, energy dependency) associated with fossil-fired electricity generation, VRE's value in avoiding these externalities is not fully reflected in electricity pricing [70]. This represents a fundamental market failure. Emission standards regulation is often criticized for legitimizing pollutant levels below the prescribed emission limits without pricing their external costs [71]. Even when there are externality-pricing schemes (e.g. pollution tax or cap-and-trade), the price level is often insufficient to fully internalize all external costs. An often cited-case is the EU emission trading scheme (ETS). Its carbon price (per Tonne CO₂) only oscillated between 6.4 and 8.6 Euro₂₀₁₅⁹ in 2015, compared to a social cost of carbon (SCC) at 108 Euro₂₀₁₅ estimated by the Stern Review and a minimum carbon price required at 61 Euro₂₀₁₅ to make VRE investments break-even [72,73]. Secondly, **explicit and/or implicit subsidies for fossil fuels**, as market distortions, also reduce the revenue of VRE relative to fossil-fired electricity generation [6]. The total global subsidies for fossil fuels amount to 516 billion USD₂₀₁₅ in 2014, equivalent to a negative carbon price of 116 USD₂₀₁₅/Tonne CO₂ [64].¹⁰ This subsidy can be substantially increased, if costs associated with military operations and diplomatic activities to secure overseas fossil resources are included [71]. Thirdly, due to historical prioritization of development, fossil fuel industries as incumbents have large **vested interests** in maintaining their competitive advantages over VRE in terms of subsidies, existing physical infrastructure and incomplete internalization of externalities [74]. They also have more political power and lobbying capacity to hinder potential policy efforts that aim to establish a level playing field for VRE [46].

Support policy schemes for VRE investments can be justified by compensation for the positive externality of technology spillover, a market failure, and the unlevelled playing field [75–77]. These schemes target VRE investments either based on each unit of electricity production or installed capacity. They play an essential role in enabling VRE investments break-even. Hence, **insufficient support levels** can lead to revenue insufficiency. Often it is caused by **constrained government budgets**, especially under austerity measures of fiscal policy [78,79]. For instance, Van der Elst and Bosch [80] observed that limited budgets under the Dutch SDE + scheme have led to under-bidding for support application.

Many investment decisions will be finally rejected, once the project viability becomes clear [80]. A similar case is also reported for PV projects in China [81].

Negative interactions between the electricity market and policies and between different policies, if not minimized, may also contribute to revenue insufficiency. Two mechanisms are often reported for such interactions. One mechanism is that **in absence of an ex-post cap adjustment mechanism**, VRE support schemes reduce the demand for emission permits under a cap-and-trade scheme [82]. This results in a decreased carbon price and electricity spot price, as observed in the EU ETS [75,83]. The other mechanism is related to the direct distortion effect of various **production-based support schemes** (e.g. feed-in tariff, feed-in premium and tradable green certificates) on the electricity market, which leads to a depressed spot price [84]. Both interaction mechanisms increase the support level required for VRE investments.

Besides revenue insufficiency, revenue volatility also negatively affects the financial appraisal, since it tends to lower the NPV-at-risk value. Three factors contributing to revenue volatility of VRE investments are often reported in the literature. Firstly, due to the **merit-order** and **decreased temporary correlation effects**, spot price volatility tends to increase with increased VRE penetration in the electricity market. Secondly, price volatility is an inherent characteristic of **quantity-based policies** for pricing externalities (e.g. cap-and-trade scheme) or supporting VRE (e.g. tradable green certificate) [85]. These are expected to increase the revenue volatility of VRE investments. Large price volatility has been observed in the EU ETS and the Swedish/Norwegian green certificate market [83,86]. Last but not least, revenue volatility also depends on the **type and features of support schemes**. Under the same mean value of annual total revenue, feed-in premiums (with fixed premiums on top of the spot price) result in higher volatility than feed-in tariffs (with guaranteed price) [87]. However, design features such as price floor and cap may limit the higher volatility associated with feed-in premiums [88,89]. Tradable green certificates can result in the highest revenue volatility for VRE investments [90]. Although feed-in tariffs provide the most stable revenue, they are increasingly replaced by other support schemes to stimulate improved market integration. For instance, the EU will prohibit the use of feed-in tariffs to support new VRE installations from 2016 onwards [91].

3.2.5. High discount rate and additional strict cut-off investment criteria

The discount rate is the minimum required rate of return demanded by the project developer, and it represents the present time-value of future cash flows. A high discount rate can be considered a barrier to VRE investments, since it leads to low or even negative NPV. Based on survey and literature data, Oxera [40] reports the range of (pre-tax) real discount rate used by investors in the United Kingdom for different VRE technologies, against that for Natural Gas Combined Cycle (NGCC) (see Fig. 4). Although only reflecting the situation in the United Kingdom, it shows that VRE investments might face a higher discount rate than fossil-fired electricity generation. As VRE investments are comparatively more capital-intensive, their NPV calculation is more sensitive to high discount rates. Therefore, a higher discount rate further exacerbates the comparative disadvantages.

The discount rate should at a minimum reflect the **weighted costs of capital (WACC)** or financing costs of the underlying VRE investment. Therefore, the discount rate increases with the WACC. Companies commonly determine WACC based on the capital asset pricing model (CAPM), which adjusts the risk-free rate based only on systematic risks – risks correlated with overall macroeconomic

⁹ EEX European emission allowance auction (EUA) market data (<https://www.eex.com/en/market-data/emission-allowances/auction-market/european-emission-allowances-auction#1/2016/06/20>).

¹⁰ Original data are converted into their constant USD₂₀₁₅ value.

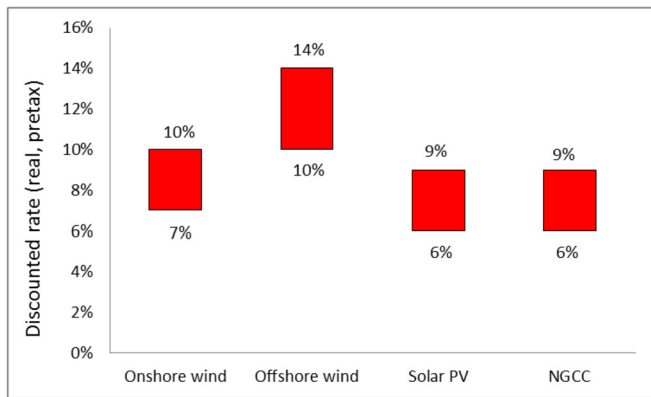


Fig. 4. Discount rate ranges for investments in different VRE technologies and NGCC. Source: data derived from Oxera [40].

conditions and business cycles [40]. Due to relatively underdeveloped capital markets, less stable macroeconomic conditions and state of political environments, and higher inflation, VRE investments in developing countries usually face a WACC substantially higher than that in developed countries [10,13]. Angelopoulos et al. [89] also reports that in the case of onshore wind investments throughout different European countries, the WACC is highest in Greece and Croatia (12%), while lowest in Germany (3.5–4.5%).

The CAPM assumes sector/firm/project -specific unsystematic risks (e.g. revenue volatility associated with input estimates, weather-related resource risks, technology risks) can be fully diversified away without additional costs. In practice this is hardly the case for VRE investments [92]. One explanation is the lack of insurance coverage due to insufficient loss data and high complexity due to the involvement of several project partners, which is particularly the case for offshore wind projects with relatively short track records [93]. Financial theories suggest that unsystematic risks should not be compensated to avoid double counting, since they are already covered through adjusting for the cash flows in the probabilistic DCF approach [94]. However, in practice risk premiums adjusted for unsystematic risks are often added on top of the WACC [40,95]. Such a practice of “**Fudge factors**” artificially increases the discount rate,¹¹ potentially reducing the NPV of VRE investments and increasing the support level needed. A typical example is the use of a risk-adjusted discount rate to compensate for the revenue volatility (an unsystematic risk) associated with different VRE support schemes, as mentioned by Kitzing [87]. This can result in a higher discount rate for feed-in premium schemes than that for feed-in tariff schemes at the same mean revenue level. Finon [53] also argues that in the SRMC-based spot market the self-hedging ability to price volatility is very limited for capital-intensive VRE investments, because of the large gap between their SRMC and long-run marginal costs (LRMC). This increases the risk of unrecovered upfront capital costs (downside risk) and, consequently, the discount rate [53].

In presence of many unsystematic risks that are unmeasurable unknown unknowns (e.g. policy uncertainty risks, social acceptance risks, spot price uncertainty risks), fudge factors can be partly, if not fully, justified. Risk premiums that are fed into the discount rate increase with the level of risk perception. In particular, **policy uncertainty risks due to discontinuity of existing support schemes**

and the lack of long-term policy visibility can have substantial and long-lasting impacts on the risk perception towards VRE investments, which increases the risk-adjusted discount rate [21,39,96]. For instance, the imposition of retroactive tariff reduction for existing VRE projects almost shut down new VRE investments entirely in Spain in 2013 [97]. As demonstrated by Luthi and Prassler [98]; wind project developers in the EU and the US also rank legal security as the most important factor in their investment decision-making [99]. In addition, insurance coverage for policy uncertainty risks barely exists [93]. If project developers are incapable of managing the perceived highly unknown levels associated with VRE investments, they may use a very high discount rate or **additional strict cut-off investment criteria** (e.g. high IRR and short PBP) to exclude the investment decision.

3.3. Barriers at project development stage

Barriers at this stage hinder the completion of necessary project development steps, and they can be split into two elements: high development costs (section 3.3.1) and lack of social acceptance (section 3.3.2).

3.3.1. High development costs

Before access to external capital, costs associated with different project development steps have to be covered by the developer's own financing resources [21]. Therefore, high development costs can be a barrier to VRE investments. **High development costs may exacerbate revenue insufficiency**, as the project developer tends to demand a higher level of support to compensate for the reduced profit margin [99]. In particular, costs associated with procedures of permits acquisition and grid connection constitute a significant part of project development costs. These costs are usually inflated by complex administrative permitting procedures, excessive power quality demand and unfavorable allocation of grid costs.

- Lengthy administrative permitting procedures

Lengthy administrative permitting procedures can significantly increase the project lead time, required efforts and human resources, resulting in increased development costs [99]. They are reported as the primary concern affecting investment decision-making for European solar PV project developers [99,100]. Lengthy permitting procedures are often prolonged by bureaucracy, non-streamlined procedures, lack of transparency or a clear timeline, the involvement of a large number of authorities and a lack of coordination between involved authorities [10,11,101,102]. This is especially relevant to offshore wind [93].

- Excessive power quality demand

As non-synchronous generators, VRE generators are connected to the grid via power electronics instead of electro-mechanical links [103]. Unlike fossil-fired synchronous generators, they alone lack capabilities for power quality control, such as system inertia, reactive power and voltage support, transient stability and fault ride-through capability [104,105]. To maintain grid stability, the grid code may demand VRE to install additional equipment for power quality control before the issuance of grid connection permits [106]. If such demand becomes excessive, it may incur high costs for the project.

- Unfavorable allocation of grid costs

Due to relatively remote locations, VRE projects typically incur higher costs associated with grid connection and the reinforcement

¹¹ Note that if capital providers also adjust their required rate of return to unsystematic risks, their fudge factors will be fed in to the WACC. It will result in an even higher discount rate.

of the existing grid [107]. Thus, unfavorable allocation of grid costs can increase development costs. In general, four prototypical allocation approaches can be distinguished, i.e. deep approach, hybrid approach, shallow approach and super-shallow approach, depending on the extent to which grid costs have to be borne by the developer [107,108]. In the deep approach, the developer pays for all costs; while only grid connection costs are paid in the shallow approach. In the super-shallow approach, all costs are socialized. Since it is difficult to disentangle the marginal impact of a new VRE project on grid reinforcement requirement, deep and hybrid approaches may unfairly increase the financial burden for the developer [108] and [14]. Even if a shallow approach is adopted, grid connection alone can still incur significant costs, especially for offshore wind projects far away from shore [108].

3.3.2. Lack of social acceptance

The lack of social acceptance ranges from spontaneous protests, professional campaigns and even legal suits [109]. It often causes delays in project development (especially the permitting step) and the escalation of development costs, which discourages VRE investments [101,110]. A high risk perception of social acceptance may also lead to the early rejection of investments at the preliminary risk scanning stage, or a high discount rate in the economic appraisal process [89]. Social acceptance towards VRE investments can be distinguished into two dimensions: generic public acceptance at consumer level and local acceptance at community level [101].

- Lack of public acceptance

Because of its environmental benefits, public acceptance today for VRE is generally high in major western economies and China [111–113]. Such acceptance is positively correlated with people's knowledge of VRE, and with education and income levels. This is reflected in the surveyed willingness-to-pay [111,114]. However, **either too high or substantial increase of support costs** for VRE can negatively impact public acceptance [79]. This is particularly the case if an additional surcharge in the electricity bill (instead of public budgets or tax-financed funds) is used to finance support costs, e.g. in most European countries [79]. It directly increases the perceived financial burdens of residential end-users and can be socially regressive [115,116]. Due to the **merit-order effect**, the surcharge level tends to increase with increased VRE penetration. In Germany it increased from 0.011 Euro/kWh to 0.053 Euro/kWh between 2008 and 2012, which has already been declared as too high by more than 51% of Germans [117]. The high and rapid increase of the surcharge is also explained by the exemption of energy-intensive industry and a large proportion of commercial users [117]. This form of **distributive unfairness** may further endanger public acceptance.

- Lack of local acceptance

Deployment of VRE projects cannot avoid negative local outcomes. Visual impact on landscape, noise and depreciated property value are associated with wind projects, while solar projects can cause heat island effect (mainly in semi-arid lands) and natural habitat losses [118–120]. These impacts tend to increase with project size and often lead to strong opposition by local stakeholders. For instance, local protests forced the withdrawal of the Palen CSP project in California, even though it had been priorly approved by state regulators [121]. This lack of local acceptance is often cited as “not in my backyard” (NIMBY) syndrome, although this may oversimplify the actual motives of locals [120,122]. Better explanations include **perceived impacts** and **perceived unfairness**

by locals [18,110,118,122]. Perceived local impacts of VRE projects can be amplified by **sub-optimal spatial planning** and **misinformation** [123]. Communication with local stakeholders including the provision of credible information and figures corrects misinformation, but its effectiveness can be reduced due to **mistrust** of locals towards the (external) project developer [123]. Highly complex, non-transparent or inaccurate information, frivolous attitudes towards locals' fears and overlooking long-term relationships with the community all undermine such trust [118]. Perceived unfairness includes unfairness associated with the distribution of negative and positive outcomes (i.e. distributive unfairness) and unfairness related to the treatment of relevant stakeholders in the decision-making procedure (i.e. procedural unfairness) [122]. Procedural unfairness, distributive unfairness and mistrust often reinforce each other. Factors contributing to distributive unfairness include the use of universalistic resources (e.g. money) to compensate for losses of particularistic resources (e.g. landscape impact) due to VRE deployment, limited distribution of project profits to stakeholders or distribution to a small number of stakeholders, and the exclusion from financial participation of stakeholders [118]. Procedural unfairness is affected by limited participation opportunities (e.g. information, consultation, cooperation) and untimely involvement of locals in project development [18,118,124].

3.4. Barriers at capital access stage

At this stage, the project developer has to access sufficient and affordable capital to finance the investment before the approval of the FID. Financing can be either on-balance sheet corporate financing, or (limited or non-resource) project financing secured against the future project cash flows. Project financing has been increasingly used in the renewable energy sector, and it accounted for 52% of total renewable energy investment in 2015 [2]. Due to limited retained earnings reserved for re-investment,¹² both corporate financing and project financing require external capitals in the form of debt and equity¹³ [7,9]. A high WACC can be caused by **high risk perception of capital providers** towards VRE, reducing the project's economic appeal and its affordability to access capital [125]. Barriers at this stage mainly include the lack of equity and the limited access to bank lending.

3.4.1. Lack of equity

The lack of equity for renewable energy investments was previously only a problem in non-OECD countries [21]. In OECD countries, the post-recession macro-economic uncertainty has caused conventional equity investors to favor investment in government bonds with high credit ratings [126]. Investors in VRE projects often include small and medium-sized utilities (e.g. in Germany) [127], but their ability to access equity financing is relatively limited [126]. In Europe, senior executives in the renewable energy sector have expressed concerns over whether sufficient equity is available to finance the offshore wind prescribed by the EU's 2020 national action plans [27]. Due to the lack of equity, VRE projects have to rely on a large amount of debt to leverage investments. Although such leverage reduces the WACC (cost of debt is generally lower than cost of equity), still a minimum equity

¹² Retained earnings account for 2/3 and 1/4 of energy sector corporate financing in OECD and non-OECD countries, and they account for only 2.9% total asset financing for renewable energy investment (excluding large hydro) in 2015 [5,7].

¹³ A few financial vehicles have emerged in recent years, such as corporate/project green bonds, institutional investors, crowd funding and YieldCos, but they are currently marginal and under-developed, especially in developing countries [7,97].

ratio in total capital is required by debt holders (because of the risk concerns of debt holders and the senior nature of debt), which is typically 15% in OECD countries and 40% in non-OECD countries [9,128].

3.4.2. Limited access to bank lending

Bank lending is the leading external source in financing renewable energy investments. Many national and international development banks have established specific programs targeting renewable energy financing with favorable lending rates. However, loans provided by development banks are limited, because they cannot autonomously create credit (i.e. money) and they have to rely on raising capital from secondary markets [125]. Commercial banks create credit to provide loans, but they can be biased against VRE investments due to the perception of unattractive risk-return profiles and relatively short track records [125,129,130]. Moreover, VRE investments, featuring typically smaller nameplate capacity than fossil-fired electricity generation, tend to face disproportionately **higher due diligence costs** to obtain loans from commercial banks, due to the significance of economies of scale [21,54]. This may exclude small and medium projects to access bank loans [21,131]. Last but not least, access to bank lending is affected by **side-effects of monetary policy**. To date, many central banks (e.g. Eurozone, Japan) have introduced a negative interest rate policies to address excess liquidity and stimulate economic growth [132,133]. This seems to increase the incentives for lending and be beneficial for VRE investments. However, empirical evidence shows that it has actually increased the lending rate in economically underperforming countries, especially in vulnerable countries (e.g. Italy, Spain, Portugal) which experienced severe stress during the recession [132]. This is because banks in these countries have a limited ability to pass on profit losses resulting from negative rates to their depositors, and they tend to charge a higher lending rate to compensate for the reduced profits [132],[134]. Post-recession macro-prudential regulations, such as Basel III at the global level and Solvency II at EU level, can also tighten the terms and conditions for financing renewable energy, because they focus on banks' short-term liquidity, solvency and stability [7,125,129]. They are expected to significantly reduce both the availability and period of bank lending [129]. Eckhardt [135] has estimated that the maximum bank lending period in the future is likely to be below seven years [129]. This is especially harmful for capital-intensive VRE investments that require long-term financing (typically 12–15 year) to cost-effectively spread the upfront costs over their operating lifetime [128].

4. Synthesis and policy implications

This paper develops an integrated framework that analyzes barriers to VRE investments through a literature review-based analysis. The framework covers most barriers to VRE investments identified in the existing body of literature. Fig. 5 presents an overview of this framework, where each box represents a specific barrier elaborated on previously, and the arrow establishes the causal-relationship between two barriers. This framework connects barriers to different stages of the investment decision-making process which is closely related to the project life of VRE assets. Thus it expands the knowledge base on the key mechanisms through which different barriers hinder the realization of VRE investments and enables relevant stakeholders to better diagnose these barriers. Policy implications can also be drawn from the consultation of such a framework. They can help policy-makers and regulators to design effective instruments to address the barriers and safeguard necessary VRE investments consistent with the 2 °C climate target.

The framework confirms the importance of risk reduction for VRE investments, as suggested by a few authors (see e.g. Refs. [89,136,137]). It shows that most barriers can find their impacts, either directly or indirectly, on the economic appeal of VRE investments, which is reflected in the reduced expected NPV or NPV-at-risk value. Barriers in the iterative economic appraisal process chiefly exhibit a negative effect over the sufficiency and/or volatility of the expected revenue, while barriers at other decision-making stages tend to increase the project developer's risk perception and be ultimately fed into the discount rate. To address the impacts of these barriers, policy-makers should design instruments that can improve the risk-return profile of VRE investments. This requires not only the mitigation of actual risks (e.g. social acceptance risks, policy uncertainty risks, revenue volatility risks), but also the addressment of psychological, behavioral and institutional attributors that increase the risk perception. Effective risk reduction necessitates more stable and credible policy instruments that can deliver long-term visibility. They should also be able to target multiple stakeholders involved in VRE investments, including the project developer, capital providers, the general public and locals. Risk reduction can have multiple benefits that contribute to a positive investment decision. In addition to increasing the economic appeal of the project, it increases the chance of progressing the project from investment intention to development action during the preliminary risk scanning stage. Furthermore, It can accelerate the completion of the project development stage and reduce development costs. A reduced risk profile also increases the willingness of capital providers to finance the VRE project at the capital access stage.

Following the integrated framework, two additional main policy implications can be drawn:

Firstly, barriers at different decision-making stages can be distinguished into what we call “**symptomatic**” and “**fundamental**” barriers. The former describes a specific symptom or phenomenon that hinders the decision-making process to move forward, while the latter is the root cause behind this symptom. With the help of arrows in Fig. 5, they can be easily identified. Symptomatic barriers can be addressed through policy instruments targeting the symptom itself or fundamental barriers that cause such symptom. We argue that addressing fundamental barriers is more effective and has more long-lasting effects when compared to only addressing the symptomatic barrier. For instance, as a symptomatic barrier, revenue insufficiency can be addressed by subsidies from support policy schemes, which can have rapid effects. This solution alone cannot solve the fundamental causes of the symptom, (e.g. unfavorable electricity market conditions, unfavorable policy and the lack of level playing field). We have shown that if not carefully designed, it may even exacerbate the fundamental barriers (e.g. through price distortion effect of production-based support schemes), increase the subsidy level needed, and cause other side-effects (e.g. increased surcharge levels for consumers). Instead, solving fundamental barriers (through establishing a level playing field, directly targeting market failures and adapting the electricity market to increased VRE generation) can eliminate these concerns.

Secondly, when designing instruments to support VRE investments, policy-makers should not overlook negative interactions with other policy instruments or with the well-functioning of the electricity market. Negative interactions not only undermine the effectiveness of a single policy instrument, but also reduce efficiency of the overall policy mix. This research demonstrates that macroeconomic policies can have negative impacts on VRE investments. For instance, austerity measures in fiscal policy can constrain government budgets, reducing the support level for VRE investments. Side-effects of monetary policy (e.g.

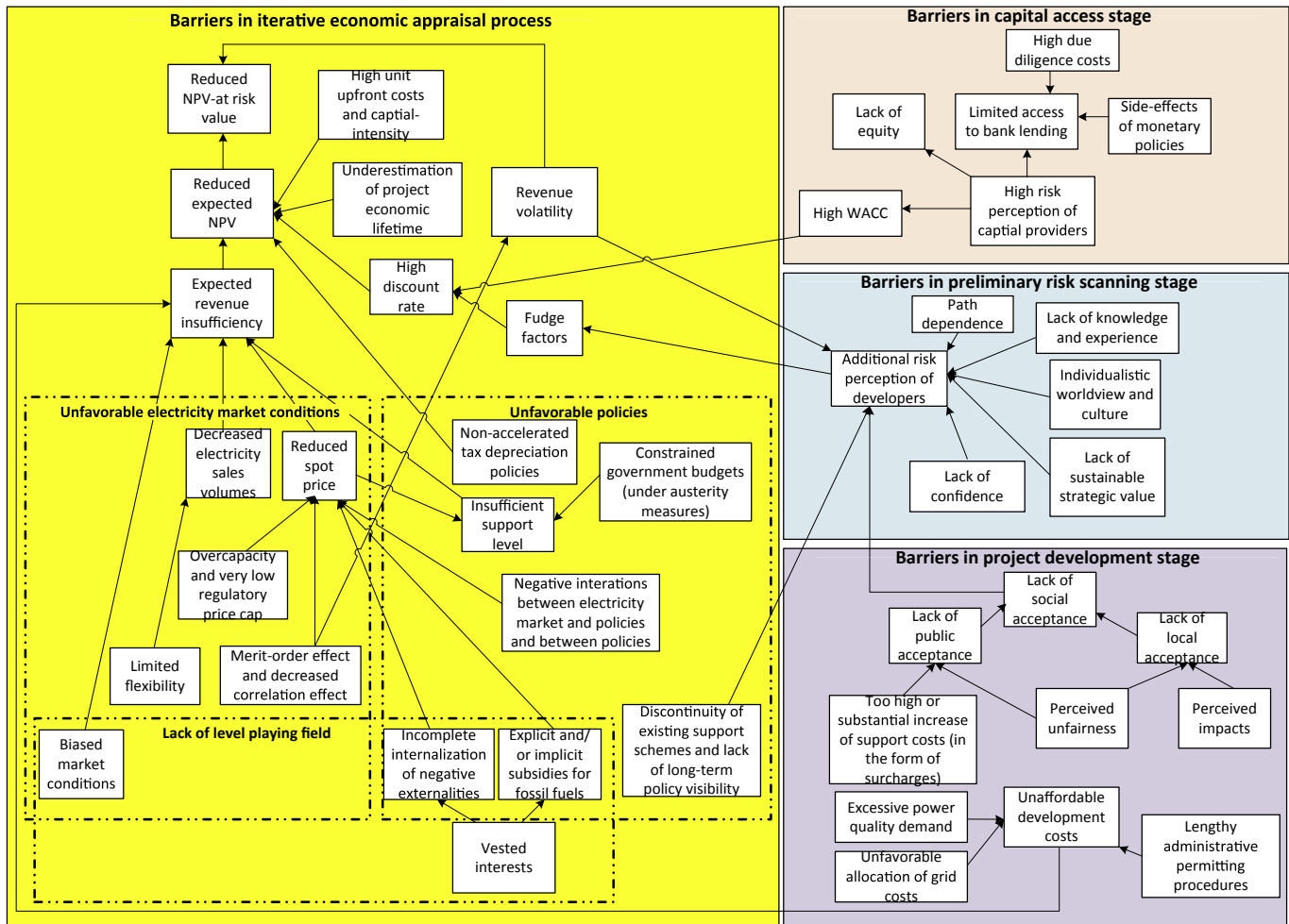


Fig. 5. Overview of the integrated framework for barriers to VRE investments.

negative interest rates, macro-prudential regulations) can increase the lending rate and decrease the availability of bank loans for VRE investments. Therefore, the authors argue that a comprehensive policy framework to support VRE investments should not be only limited to the narrow context of climate and energy policy and the electricity market. It should be incorporated into a broader context that also includes monetary and fiscal policies. When redesigning these macroeconomic policies, their potential negative impacts on other policy objectives (e.g. energy transition and VRE investments) should be considered and corresponding measures should be taken to minimize these impacts.

5. Recommendations for further research

This paper provides a comprehensive and up-to-date review-based analysis of barriers to VRE investments, based on the development of an integrated framework that represents different stages of the investment decision-making process. Different barriers identified from the existing body of literature and their causal-relationships are well-integrated into such a framework. However, the developed framework can be improved in a few aspects. This also illuminates directions for further research.

First, this framework connects barriers to VRE investments with the investment decision-making process, based on the underlying rationale that barriers increase the likelihood of the investment decision being rejected. It allows the identification and analysis of

different types of barriers from existing literature sources, as well as their attributes and relationships, in a straightforward and qualitative manner. However, application of this framework alone is insufficient to disclose the relative size and significance of each identified barrier in terms of the impact on investment decision-making. To complement this research, the authors suggest further studies to quantitatively assess this aspect. These could be conducted through a case study or a survey-based logistic regression analysis. These studies would also be supportive to verify and refine the developed integrated framework that represents the investment decision-making process.

Second, the framework is developed to represent the investment decision-making process for VRE investments, where facing the three states of unknowns (i.e. risks, uncertainties and ignorance) is inevitable. While ignorance is barely conquerable and should be treated warily at best, the framework in this paper assumes (unquantifiable) uncertainties can be reduced to (quantifiable) risks through assigning a (subjectively) estimated probability. Such a reductionist approach allows the application of probabilistic models (e.g. Monte Carlo simulation) to tackle uncertainties in investment decision-making, especially in the economic appraisal process. Despite its convenience, this approach cannot fully tackle uncertainties in the case of events associated with probabilities that cannot be estimated, and the existence of more than one possible probability distribution. A complementary scenario analysis appears to be capable of addressing this issue and it can include

unpredictable system-wide structural change events (e.g. changing the infrastructure of the energy system, changing the rules of the electricity market, changing subsidy schemes) into the decision-making process. Under different scenarios, the relevance of each barrier identified in this paper can differ. Low reliability of the input parameters (e.g. for the economic appraisal) also gives rise to uncertainties in the investment decision-making. The combination of a qualitative pedigree analysis and a quantitative sensitivity analysis can better deal with such uncertainties [138]. To take all these into account, the authors propose further model-based studies to develop algorithms which can better allow for uncertainties in the investment decision-making process.

Third, because of zero direct emission, VRE investments are considered more environmentally sustainable than fossil-fired electricity generation projects. Hence, the developed framework in this paper mainly focuses on the risk and economic aspects of investment decision-making from the project developer's perspective. However, from a broader view of sustainability, the environmental and social aspects throughout the entire life cycle (including the supply chain) of the underlying VRE investments are as equally important as the economic aspect. Accomplishing certain steps of the project development stage (e.g. EIA and permits acquisition) usually requires a certain level of social and environmental performance of VRE investments, but it is not sufficient to guarantee a high level of sustainability. Although more stringent sustainability criteria are not mandatory for VRE investments (and thus do not constitute barriers), they are expected to be respected. These criteria can include a low embodied energy/emission; a short energy/emission payback period; limited impact on biodiversity; and the use of locally available supply chain, labour and feedstocks etc. To incorporate sustainability criteria into VRE investments, a multi-criteria decision-making process can be established. An accompanying full life cycle assessment (LCA), which includes Environmental LCA, Social LCA and Life-cycle cost analysis, is needed to support such decision-making. Future studies are recommended to explore this area.

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