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Valuing trade-offs between renewable energy and ecosystems

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Abstract

In pursuit of a more sustainable economy and society, policies worldwide support the renewable energy transition and the protection of natural ecosystems. While these goals tend to be viewed independently, renewable energy development can disrupt ecosystem processes. Due to their interactions with natural resources such as water and biomass, hydropower and biogas exemplify this tension. Hydropower plants can alter the flow, level and temperature in water bodies, which can lead to changes in ecosystem processes. Similarly, the development of biogas has stimulated the cultivation of energy crops, which can directly compete with food production and decrease farmland biodiversity. In light of this tension, this dissertation aims to value trade-offs between renewable energy and ecosystems in four empirical studies.

The first study investigates stakeholder preferences for biogas development. As German renewable energy policy has been lauded as a model for others, the expiration of the biogas feed-in-tariff scheme offers an interesting setting for understanding how stakeholders believe the sector should progress. The results indicate that support mechanisms should only compensate for specific benefits such as flexibility, special feedstock or heating to reduce tension between biogas and non-biogas farmers. The second study shifts the attention to hydropower and compares public values about run-of-the-river (RoR) hydropower in Germany, Portugal and Sweden. As a large share of future hydropower in Europe will use RoR schemes, its development represents an opportunity for sustainable decentralization. The results indicate strong preferences for regional control, citizen well-being and ecological measures, which implies that RoR hydropower should be managed as a source of distributed generation and that operators should adopt mitigation strategies that deliver both ecological and societal benefits. Given that mitigation strategies can be costly and reduce power production, the third study focuses on the economic trade-offs between the restoration of fish passage and hydropower production. We find that power losses do not account for a large share of lifetime mitigation costs, nature-like fish passes incur lower costs overall and there is limited information about monitoring costs. To quantify benefits of mitigation, the fourth study measures the public's willingness to pay for ecological measures and monitoring at hydropower plants. The results indicate strong support for fish protection and monitoring as well as opposition to foreign ownership. Additionally, two supplementary studies investigate links between climate change and smallholder vulnerability and empowerment in South Asia. Overall, the results of this dissertation highlight the importance of valuing externalities associated with ecological mitigation for renewable energy to increase its use, acceptance and diffusion.

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List of Abbreviations

AIC	Akaike Information Criterion
BIC	Bayesian Information Criterion
CPI	Consumer Price Index
EEG	German Renewable Energy Act / Erneuerbare-Energien-Gesetz
DCE	Discrete choice experiment
IPCC	Intergovernmental Panel on Climate Change
LCA	Latent class approach
LCOE	Levelized cost of electricity
LCOM	Levelized cost of mitigation
MNL	Multinomial logit model
NGO	Non-governmental organization
PCA	Principal component analysis
RE Directive	Renewable Energy Directive
REML	Restricted maximum likelihood
RoR	Run-of-the-river hydropower
RUM	Random Utility Maximization
WFD Directive	Water Framework Directive
WTP	Willingness-to-pay

1.0 Introduction

Environmental policy around the world focuses on the transition to a higher share of renewable energy production and the protection of natural ecosystems. In Europe, this is reflected by mandates such as the Renewable Energy Directive (2009/28/EC), the Water Framework Directive (2000/60/EC) and others. While these goals tend to be viewed independently, renewable energy development can disrupt ecosystem processes. Thus, it is crucial to examine and value trade-offs between ecosystems and renewables. The following sub-sections describe the European policy context, challenges of balancing renewables with ecosystems and objectives of the dissertation.

1.1 Renewable energy and environmental policy in the European Union

In light of rising global energy demand, there has been increasing interest in renewable energy sources to mitigate climate change and reduce fossil fuel consumption (Edenhofer et al., 2011). Within the Paris Agreement, which established the goal of limiting the global average temperature increase in this century below 2°C, the parties agreed to outline and communicate their planned nationally determined contributions to reduce greenhouse gas emissions (United Nations Framework Convention on Climate Change, 2015). As the basis of such agreements is the use of low-carbon energy, many countries have promoted the development of renewable energy technologies through national energy plans to reduce their greenhouse gas emissions (Gielen et al., 2019; Moriarty & Honnery, 2016). Renewable energy technologies include bioenergy, solar, geothermal, hydropower, ocean energy and wind energy (Edenhofer et al., 2011). Renewables have the potential to mitigate climate change and generate positive externalities or "co-benefits" as coined by the Intergovernmental Panel on Climate Change in its 3rd Assessment Report (IPCC, 2001), including supporting energy security, rural development and employment opportunities (Helgenberger & Janicke, 2017). However, renewable energy development can disrupt ecosystem processes and natural resource management can hinder the expansion of renewables.

In the European Union, the Energy Action Plan of 2007 and the Renewable Energy Directive (DIRECTIVE 2009/28/EC) are central to energy policy (European Union, 2009; Pepermans, 2019). The Energy Action Plan focuses on security of supply, competitiveness and environmental sustainability, which are now reflected in the European Commission's strategy of 2015 (Eurostat, 2019). Under the RE Directive, member states must receive at least 10% of transport fuels from renewable sources. Further, they must meet the mandatory community target of increasing the share of renewable energies in gross final energy consumption to 20% by 2020. In accordance with the directive, member states established national targets dependent on their individual conditions (European Union, 2009). After 2020, national targets were abolished and renewable energies were promoted by increasing the target to 27% by 2030 (European Commission, 2014). In the recast Renewable Energy Directive (DIRECTIVE 2018/2001/EU), the target was increased to 32% by 2030 (European Union, 2018).

In Germany, the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG) has provided the legislative framework for renewable policy since 2000. Key components of the EEG include requirements for suppliers to feed electricity from renewable energy sources into the grid, prioritization of electricity from renewable energy sources over conventional sources (merit order), the establishment of minimum regressive remuneration and a shift of costs from the supplier to the final consumer (BGBL, 2000, 2004, 2009, 2014). Since 2000, it was revised in 2004, 2009, 2012, 2014 and 2017 (BMWI, 2020). The most notable change to the remuneration system was in the EEG 2017 as tender processes rather than the state determined the level of remuneration (BMWI, 2020).

In terms of environmental policy, the European Union's Water Framework Directive (WFD) was adopted in 2000 with the aim to achieve good status in rivers, lakes, transitional waters, coastal waters and groundwater by 2027 (European Parliament, 2000). While environmental targets for natural water bodies are clearly defined, goals for heavily modified water bodies, where hydropower plants are often located, are the subject of ongoing policy discourse (Kampa et al., 2017). The European Union has also established natural and biodiversity protection policy within the Biodiversity Strategy to 2020, which encompasses the Birds Directive (78/409/EEC13) and Habitats Directive (92/43/EEC12). Additionally, a European ecological network of conservation areas has been established under Natura 2000 site protection. To establish conservation objectives, the Habitats Directive recommends using Natura 2000 management plans. Project development (e.g., hydropower modernization) is particularly limited within Natura 2000 sites as projects are subject to detailed impact assessment. In special cases, projects can be carried out if they are deemed imperative (Kampa et al., 2017). The Strategic Environmental Assessment Directive (2001/42/EC) aims to ensure environmental protection through rigorous impact assessments of proposed programmes and plans. Similarly, the Environmental Impact Assessment Directive 2011/92/EU focuses on impacts of individual public and private projects.

1.2 Trade-offs between renewables and ecosystems

Although renewable energy development and ecosystems interact in a number of ways, this dissertation primarily focuses on how renewable development negatively effects ecosystems. This is because few renewable energy studies consider ecosystems, thus it is important to consider this relationship to prevent renewable energy development from causing critical trade-offs between energy provision and other ecosystem services (Picchi, van Lierop, Geneletti, & Stremke, 2019). On the other hand, there is a large body of literature on the "co-benefits" and positive aspects of climate policy, including renewable development for ecosystems (Bain et al., 2016). In comparison to other renewables, hydropower and biogas have been lauded as key flexible components of a renewable energy transition and are closely linked with ecosystem processes.

To reduce negative ecological externalities, hydropower operators can implement fish passes, fish-friendly turbines, river restoration and operational changes and biogas operators can utilize waste heat as well as use alternative feedstock such as waste byproducts, manure and wild flowering plants to support biodiversity. While these mitigation strategies create positive externalities, they can also incur high costs and power losses. As both renewables also offer system flexibility, it is important to understand how ecological mitigation may reduce renewable generation.

1.2.1 Hydropower and ecosystems

The effects of hydropower on river ecosystems and biodiversity have been widely studied. Hydropower plants can lead to river fragmentation and disrupt fish migration, flow and sediment transfer (D. Anderson, Moggridge, Warren, & Shucksmith, 2015). Hydropower plants can be classified according to their head height, turbine, storage capacity, purpose and size. According to their storage capacity, the main types of hydropower projects are reservoir (significant storage), run-of-the-river (little to no storage) and pumped storage (Egré & Milewski, 2002). The different types of schemes provide different benefits for the energy system. While reservoir projects can store energy, they can also regulate downstream flow, thereby supporting the development of multiple run-of-the-river plants (Egré & Milewski, 2002). Reservoir hydropower projects can range from a few km^2 to thousands of km^2. Reservoir types have also generated significant controversy due to their environmental impacts related to construction, infrastructure, change in river flow patterns and transformation of rivers to lake environments (Egré & Milewski, 2002). In pumped storage schemes, water is pumped into an upper storage basin during off-peak hours using surplus electricity from base load plants. When demand peaks, the water is released to generate electricity and are thus considered an efficient means of energy storage (Harby et al., 2013). Environmental effects of pumped storage schemes can differ significantly by site and include impacts on both abiotic and biotic factors (M. A. Anderson, 2010). For both reservoir and pumped-storage plants, it should be noted that their reservoirs often serve multiple purposes including domestic and industrial water supply, irrigation, flood protection, fish farming and recreation (Harby et al., 2013).

In contrast, run-of-the river projects use the flow of the river to generate power. They vary in size from small head designs (i.e. on large, gently sloped rivers) to high head plants (i.e., on small, steep rivers). Since these projects depend on river discharge, their power production varies greatly over the year. While they are widely regarded as less environmental damaging, there is limited evidence of this assumption (D. Anderson et al., 2015). Particularly as run-of-the-river plants create in-channel barriers and change the flow regime, it is important to understand their impacts both individually and cumulatively over a watercourse (Larinier, 2008). As many run-of-the-river projects tend to be smaller in scale, it is also notable to discuss how size of hydropower plants relate to the environmental impact. While previous literature has assumed that size of plants is a good indicator for impact, recent studies have highlighted the flaw in this assumption. Particularly when many small plants are located on the same river catchment, their cumulative environmental effect can be more significant than a small plant relative to power production (Bakken, Sundt, Ruud, & Harby, 2012).

As compensation for these impacts, some hydropower companies have released fish but these measures are ineffective as reared fish do not always survive in the wild (Nieminen, Hyytiäinen, & Lindroos, 2017). As a result, recent policy has shifted to require other forms of mitigation in order to receive hydropower licenses (Roscoe & Hinch, 2010), including geomorphological restoration, fish passage facilities, sediment management and operational strategies. While mitigation can reduce negative environmental externalities, it can be costly for hydropower operators (i.e., construction, maintenance, monitoring, lost power production) and society (i.e., loss of flexible power). Thus, it is important for decision-makers to understand the costs as well as the benefits of such measures. On the cost side, there has mainly been literature on financial costs (i.e. planning, construction and maintenance), but limited research on economic costs associated with monitoring and power losses (Nieminen et al., 2017; Venus, Smialek, Pander, Harby, & Geist, 2020). On the benefits sides, the monetary value of benefits can be hard to measure. Thus, non-market valuation with contingent valuation or choice experiments has been used. Examples of non-market valuation for ecological hydropower include discrete choice experiments from Sweden (Kataria, 2009; Sundqvist, 2002), Portugal (Botelho, Ferreira, Lima, Pinto, & Sousa, 2017), Switzerland (Tabi & Wüstenhagen, 2017), Austria (Klinglmair, Bliem, & Brouwer, 2015) and Korea (Han, Kwak, & Yoo, 2008). Further, Mattmann et al. (2016) conducted a meta-analysis of hydropower externalities and found that there is a strong public focus on negative externalities, but a limited willingness to pay to avoid them.

1.2.2 Biogas and ecosystems

To understand how biogas and ecosystems interact, it is first important to understand the process of biogas production. When microorganisms decompose organic matter under anaerobic conditions, biogas is produced in a process called anaerobic conditions (Scarlat, Dallemand, & Fahl, 2018b). As biogas is mainly composed of combustible methane with smaller amounts of carbon dioxide, water vapour, oxygen, sulphur and hydrogen sulphide (Da Costa Gomez, 2013), it is considered a substitute for natural gas (Urban, 2013). The biomass feedstock largely determines the concentration of methane in biogas (Fardin, de Barros, & Dias, 2018). Common feedstock include substrates from farms (e.g. slurry and manure, resides and by-products, feed waste, energy crops such as maize, sorghum or clover), waste from private households and municipalities, organic waste from industry, domestic and industrial sewage sludge, forest residues and aquatic plants (Da Costa Gomez, 2013). Biogas can be used for electricity, heating and steam for households and industry as well as upgraded to biomethane to be used as vehicle fuel (Da Costa Gomez, 2013; Ullah Khan et al., 2017). Biomethane is particularly useful as it can be stored for the provision of energy in the form of heat, fuel or electricity (Budzianowski & Brodacka, 2017; Urban, 2013). Biogas has the potential to balance fluctuating renewables through “downward flexibility”, thereby compensating the positive residual load with power plants (Dotzauer, Pfeiffer, et al., 2019).

In comparison to other renewables, biogas is less location specific and can be flexibly operated on both small and large scales (Sawyerr, Trois, Workneh, & Okudoh, 2019; Weiland, 2010). Further, anaerobic digestion can have positive externalities by improving fertilizer quality of manure, reducing greenhouse gas emissions that arise from manure decomposition and decreasing nutrient runoff (Al Seadi et al., 2008; Scarlat, Dallemand, & Fahl, 2018a). On the other hand, biogas can threaten biodiversity and other ecosystem services related to energy crop rotation and leached nutrients (Dotzauer, Daniel-Gromke, & Thrän, 2019). As monocultures such as maize utilize pesticides and herbicides, they result in few ecological niches for remaining species (Dotzauer, Daniel-Gromke, et al., 2019). Further, leached nutrients can pollute groundwater if digestate is not applied properly (Dotzauer, Daniel-Gromke, et al., 2019). Thus, the alternative energy crop Silphium perfoliatum has been explored to support biodiversity given its long flowering time and soil coverage (Gansberger, Montgomery, & Liebhard, 2015). Further, the German Fertilizer Ordinance restricts the application of digestate to fields during certain times of the year to reduce nitration pollution in water (Neumann, 2019). However, maize has been found to be the most efficient and switching to other crops may reduce the performance of biogas plants (Amon et al., 2007).

1.3 Objectives and structure

As hydropower and biogas offer the potential to balance intermittent renewables, policies on both the national and regional level have fostered renewable expansion through feed-in-tariffs and other incentives. On the other hand, environmental regulation has established guidelines for mitigating negative ecological impacts, which can reduce renewable power production and incur additional costs related to construction, management and monitoring. This tension between renewable energy policy and environmental regulation highlights the need for further evidence about the costs and benefits of different strategies. The primary objective of this dissertation is to assess these trade-offs to support decision-making about renewable energy policy and environmental regulation.

Figure 1 provides an overview of the studies in the dissertation. Against the background of evolving energy policy and environmental regulation, the four studies address trade-offs between renewable energy development and ecosystems. Trade-offs are considered from the side of energy consumers, producers as well as other stakeholders. Thus, the analysis can be conceptualized as adopting a multi-stakeholder approach with a focus on preferences and valuation related to the development of hydropower and biogas at the German and European levels. The studies also consider different focuses such as sustainable decentralization as well as various policy and regulatory approaches.

The first study examines the context of evolving renewable energy policy in Germany. As German renewable energy development has been propelled by feed-in-tariffs under the Renewable Energy Act (EEG), their phase-out poses challenges for the biogas sector. While previous studies have focused on the effects of economic support for biogas on the agricultural sector, there are few studies exploring the outlook of the sector, particularly for small biogas producers. To fill this gap, the first study assesses stakeholder preferences for the trajectory of the German biogas sector.

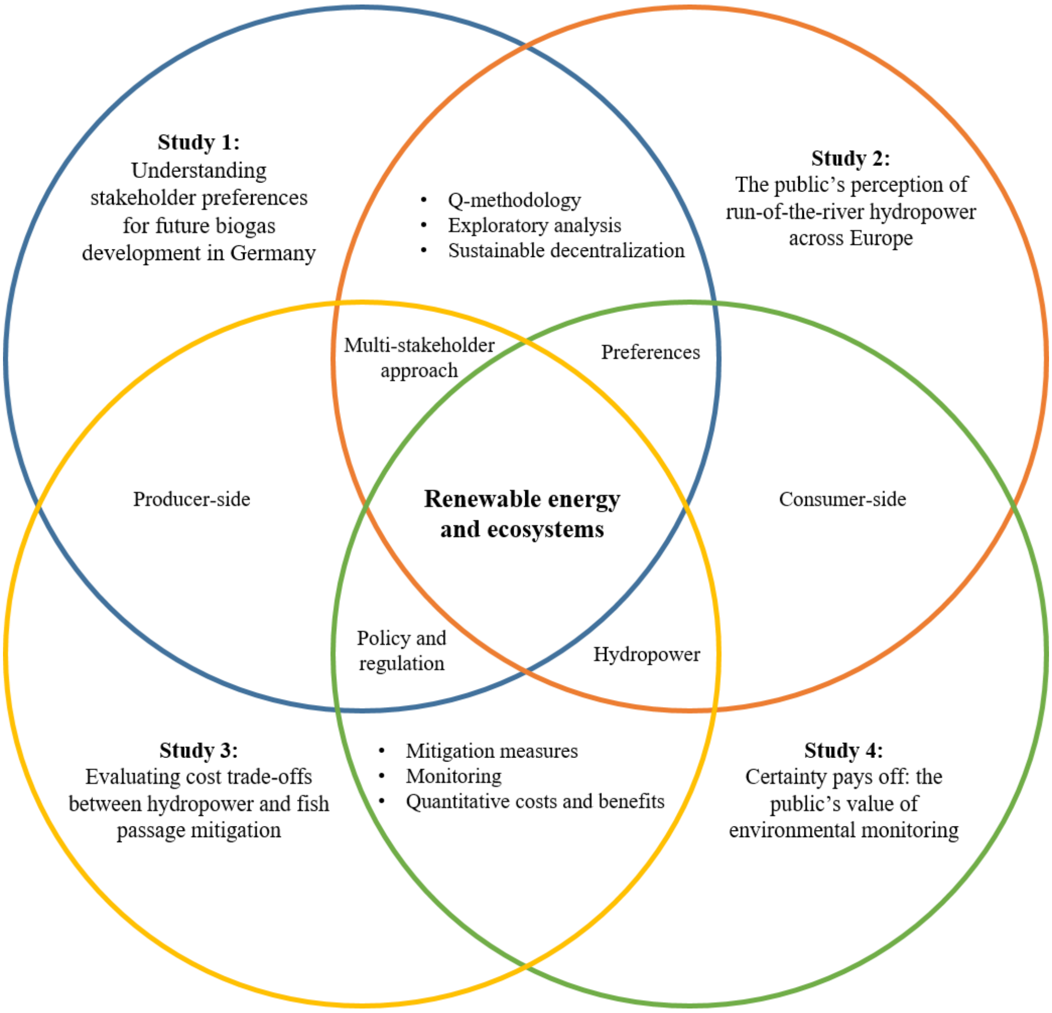

Figure 1 Overview of studies in the dissertation

The second study shifts the focus to hydropower. Given that preferences form the basis for non-market environmental valuation, this study contributes by comparing public values about run-of-the-river (RoR) hydropower in Germany, Portugal and Sweden. As a large share of future hydropower in Europe will use RoR schemes, its development represents an opportunity for sustainable decentralization. The results indicate strong preferences for regional control, citizen well-being and ecological measures, which implies that RoR hydropower should be managed as a source of distributed generation and that operators should adopt mitigation strategies that deliver both ecological and societal benefits.

Given that mitigation strategies can be costly and reduce power production, the third study focuses on the economic trade-offs between the restoration of fish passage and hydropower production. We find that power losses do not account for a large share of lifetime mitigation costs, nature-like fish passes incur lower costs overall and there is limited information about monitoring costs. To quantify benefits of mitigation, the fourth study measures the public's willingness to pay for ecological measures and monitoring at hydropower plants. The results indicate strong support for fish protection and monitoring as well as opposition to foreign ownership.

In Europe, improvements to renewable energy development and environmental policy contribute to the broader global goal of fighting climate change. As the Intergovernmental Panel on Climate Change (IPCC) declared that a temperature increase of 1.5 °C above the preindustrial level represents significant risks for natural as well as human systems, action to reduce greenhouse gas emissions through renewable energy development are key (Masson-Delmotte et al., 2018). On the global scale, climate change exacerbates existing challenges related to food security, land degradation and poverty in developing countries (Mall, Singh, Gupta, Srinivasan, & Rathore, 2006). South Asia is a region particularly vulnerable to climate variability as its economy and society are highly dependent on agriculture (Vermeulen et al., 2012). In particular, climate change threatens smallholder farmer livelihoods and empowerment by increasing extreme weather events (Kasperson & Kasperson, 2001). Thus, two supplementary studies investigate links between climate change and smallholder farmer vulnerability and empowerment in South Asia using index approaches. In the first study, we estimate the Livelihood Vulnerability Index for two districts in the Indo-Gangetic Plains, one of India's most productive agricultural regions. While both districts face similar climate exposure and adaptive capacity levels, we find that sensitivity makes one district more vulnerable to climate change and recommend that policymakers address weaknesses in infrastructure. In the second study, we estimate the Abbreviated Women's Empowerment in Agriculture Index under climate change and compare gender empowerment between two regions in Nepal. We find that climate change can reduce female empowerment and recommend that policymakers support female-oriented extension strategies and technologies. Both studies shed light on suitable climate mitigation and adaptation strategies in India and Nepal for smallholder farmers.

The following research questions are fundamental to valuing trade-offs between renewable energy development and ecosystems due to their policy relevance:

1. What are stakeholder preferences for the trajectory of the biogas sector?
2. How does the public value run-of-the-river hydropower in Europe?
3. What drives costs of ecological hydropower mitigation?
4. What is the public's value of ecological hydropower and monitoring?

This dissertation aims to answer these research questions and provide insights for decision-makers about trade-offs between renewable energy development and ecological conservation.

2.0 Conceptual framework

2.1 Challenges of non-market costs and benefits

Many environmental and ecological policies require cost-benefit assessments of different restoration and mitigation strategies. Although decision-makers can often estimate costs, it can be difficult to measure benefits because environmental goods and services are not always traded in markets. Environmental goods are often subject to market failures as they tend to be non-exclusive, non-rival or both. The types of market failures include externalities, public goods, common property resources and natural monopolies (Randall, 1983). If these values are not considered, decision-makers may inefficiently allocate resources. Thus, there is a large body of literature measuring monetary values associated with non-market environmental goods and services. This chapter reviews relevant theories.

2.2. Opportunity costs

It is possible to distinguish between financial and economic costs. Financial costs refer to costs that are based on observable prices (e.g., labor, material). In the context of ecological restoration and mitigation, these include capital, operation, management and monitoring (Main, Roka, & Noss, 1999). In contrast, economic costs capture foregone benefits that would have resulted if the resources had been used for alternative strategies. These are often conceptualized as opportunity costs. We can distinguish between private opportunity costs (i.e., costs for a single agent) and social opportunity costs. The true cost of ecological conservation capture both private and social opportunity costs from the viewpoint of those who either gain or lose from the given action.

In cases of natural resource management, opportunity costs are particularly difficult to assess as they entail non-financial values (Pearce & Markandya, 1987). In the context of hydropower mitigation, opportunity costs are foregone opportunities of using water for other profitable uses (Adams, Pressey, & Naidoo, 2010). More importantly, opportunity costs must be considered to achieve efficient resource allocation (Buchanan, 1991). This is because opportunity costs are not zero as long as some sacrifice (explicit or implicit) is required or cost is incurred (Burch & Henry, 1974).

Another challenge of non-market costs relates to externalities, which can be positive or negative. Externalities are goods and services, for which no one pays. Examples of negative externalities include pollution (e.g., from burning coal). However, pollution itself can be conceptualized as not only a market failure but a failure of private policy (Lehmann, 2012).

2.3 Market failure

Both opportunity costs and externalities lead to inefficient resource allocation. If resources are not efficiently allocated, a market failure occurs (Randall, 1983). Market failures can be classified according to the following categories: public goods, common property resources and monopolies (Randall, 1983). Within the category of monopoly, economists consider both (i) extreme market concentration and (ii) natural monopoly. Government intervention can fix market failures through taxes, subsidies and regulation. However, the challenge is to establish the correct levels each (Fisher & Rothkopf, 1989).

The challenges associated with each type of market failure can be simplified to their status as non(excludable) and non(rival). The term "public good" refers to goods which are both non-excludable and non-rival (Samuelson, 1954). Public goods are often subject to the "free-rider problem" in which those who do not pay for the good are nevertheless able to benefit from it. Examples include information and national security. Public goods can be valued by vertically aggregating all individual willingness-to-pay for the resource (WTP) (Randall, 1983). In turn, the efficient provision of a public good occurs when aggregate marginal WTP equals the marginal cost of providing the good (Samuelson, 1954).

Public goods are often confused with common goods. The term "common property resource" was coined by Gordon (1954) in his application to the "depletion" and "overexploitation" of the fishing industry. He attributed the problem of overfishing to the rights of the resource: nonexclusive but rival. As fish are not private property, no one can be excluded from their use without prohibitive costs. However, overfishing can deplete fish stocks, which makes the resource "rival".

A natural monopoly is defined as a market in which the barriers to entry (e.g. costs of infrastructure) are prohibitively high for new firms to enter the market. Examples include provision of roads, bridges, railroads, transmission lines and pipelines (Randall, 1983).

2.4 Non-market environmental valuation

As described in the previous sub-section, efficient provision of public goods can be determined by aggregating marginal willingness-to-pay for such goods. Non-market environmental valuation seeks to estimate individual willingness-to-pay. The following sub-sections describe the development of non-market environmental valuation including the history of thought, the theoretical roots of choice modelling, heterogeneous preferences and the role of risk and uncertainty.

2.4.1 History of thought

Preferences, constraints and information form an important part of neoclassical economic theory. Under neoclassical economic theory, it is assumed that people have rational, ordered preferences, which are stable and innate. These preferences can be represented in a utility function, which represents the value a person derives from an object or action. As early theorists argued, without utility, an object is believed to have no value: “An object can have no value unless it has utility” (Taussig, 1912).

An additional tenet of economic theory is rational consumer behavior, which assumes that individuals maximize their utility. Utility Theory and factor analysis both trace their roots to the scholar L.L. Thurstone, who conceptualized what is now the binomial probit model (S. Brown, 1980; McFadden, 2001; Thurstone, 1927). Many decades later, Marschak (1959) introduced this concept in economics within the Random Utility Maximization (RUM) model. Around the same time, Luce (1959) introduced the Independence from Irrelevant Alternatives (IIA) axiom, which implied strict utilities. In other words, if an individual must choose between two alternatives, the introduction of a third alternative would not change the final decision.

Under utility maximization, it is assumed that respondents facing several choices aim to maximize their utility relative to their constraints and under perfect information (McFadden, 1974). This process is often referred to as a “black box”, an unknown process that economic choice theory seeks to model (McFadden, 1986). The cognitive decision-making process in market behavior is characterized by several key components: perceptions or beliefs, general attitudes or values, preferences among goods, decision protocols to map preferences and behavior intentions (McFadden, 1986). Figure 2 traces the interactions among these components. Product attributes, previous experiences, attitudes and perceptions influence an individual’s preferences. Decision protocol and preferences influence behavior intentions, which along with market constraints determine market behavior. Thus, the chain of reasoning for non-market valuation within the utility framework links human preferences to market choices to valuation (Gowdy & Erickson, 2005).

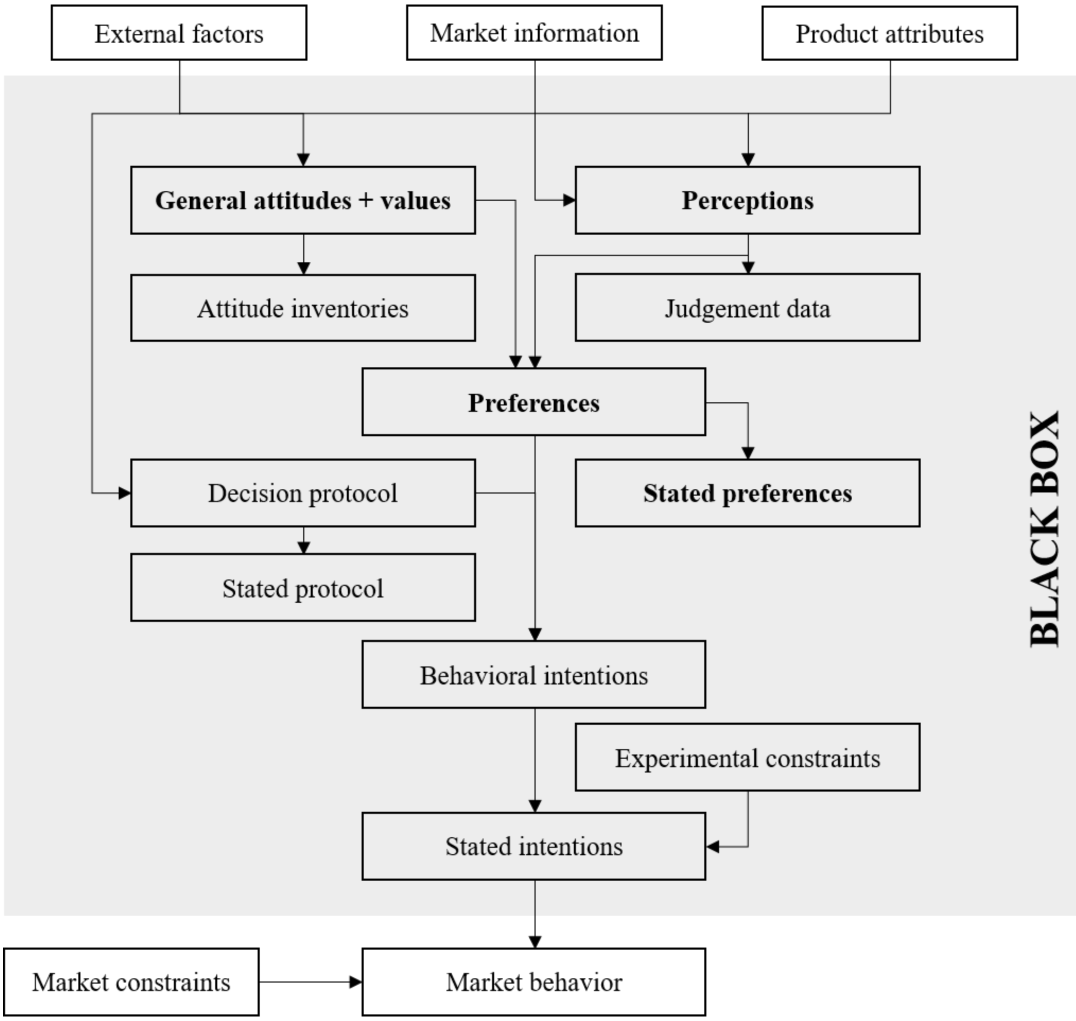

Figure 2 Map of consumer choices and market behavior

Adapted from McFadden (1986)

2.4.2 Roots of choice modelling

In early empirical studies of market demand, heterogeneous preferences were ignored. However, in the 1960s, an increase in microeconomic data availability enabled the study of individual consumer behavior (McFadden, 2001). Based on psychological studies on discrete choice behavior, McFadden (1975) proposed the conditional or multinomial logit model (MNL), which could be estimated with maximum likelihood. The model was significant because it connected unobserved preference heterogeneity to a distribution of demands (McFadden, 2001).

In turn, the random utility theory-based discrete choice models from economics were combined with concepts from other disciplines including axiomatic conjoint measurement and information integration theory from psychology and discrete multivariate models from statistics

(Hoyos, 2010; Lancsar & Louviere, 2008). Lancaster (1966) described the theory of demand, welfare theory and consumer theory, thereby laying the foundation for microeconomic models of consumer behavior (Hoyos, 2010). Based on these concepts, Louviere & Hensher (1982) and Louviere & Woodwort (1983) developed discrete choice experiments (DCE).

In the following years, applications of non-market valuation gained traction after the landmark 1989 case of Ohio v US Department of Interior, in which the court accepted use and non-use values derived from contingent valuation in damage assessment of the Exxon Valdes oil spill (Arrow et al., 1993). Later, Adamowicz, Louviere, & Williams (1994) used DCEs for environmental valuation.

Choice analysis analyzes a set of choices, in which each choice set has several alternatives based on different attribute combinations and each discrete alternative is associated with a utility level (Hausman & McFadden, 1984). The probability that a respondent will select an alternative i from alternatives j of set Cn can be expressed as:

$$P_{in} = \frac{\exp(\mu\, V_{in})}{\sum_{j \in C} exp V_{jn}} \qquad \textit{Eq.1}$$

where V_{in}/V_{jn} is the systematic component of the utility and μ is the scale parameter, which is inversely proportionate to the standard deviation of error terms.

2.4.3 Heterogeneous preferences

The basic framework assumes homogenous preferences of respondents and the independence of irrelevant alternatives (Hausman & McFadden, 1984). Given that an individual's preferences do not vary by choices (alternative-specific), it was difficult to model heterogeneous preferences within the random utility model (Boxall & Adamowicz, 2002). To account for this heterogeneity and mitigate bias, several approaches emerged including interacting individual-specific characteristics with attributes (Wiktor Adamowicz, Swait, Boxall, Louviere, & Williams, 1997), random parameter logit/probit models (Train, 1998), the mixed logit (McFadden & Train, 2000; Train, 2003) and latent class methods (Boxall & Adamowicz, 2002). These methods differ in the way they introduce heterogeneity into the estimation and the extent to which they can explain sources of it (Boxall & Adamowicz, 2002).

Among these, the two main approaches for accounting for heterogeneous preferences are the mixed logit and latent class approach (Boxall & Adamowicz, 2002). The mixed logit model assumes a continuous and random distribution of tastes. The latent class approach (LCA) which use a priori knowledge of the elements of heterogeneity and categorizes individuals into homogenous classes and posits a discrete distribution of tastes (Boxall & Adamowicz, 2002). For the mixed logit model, the utility function can be expressed as:

$$U_{njt} = \beta_n x_{njt} + \varepsilon_{njt} \qquad Eq.2$$

Where x_{njt} represents the attributes of each alternative j in choice occasion t for each respondent n. ε_{njt} is the unobserved random term, which is independent and identically distributed. β_n represents the vector of respondent characteristics, which is unknown. Thus, the unconditional choice probability is represented in the mixed logit as the integral of conditional probabilities over all possible variables. The function of this integral is assumed to follow a normal distribution. In the mixed logit model, the distribution of β_n is continuous whereas in the latent class model, the distribution is discrete based on several segments or classes. If β can be Mvalues with probability S_m that $\beta = b_m$, the choice probability in the latent class model can be expressed as:

$$P_{nit} = \sum_{m=1}^{M} S_m \left(\frac{e^{b_m} x_{nit}}{\sum_j e^{b_m x_{njt}}} \right) \qquad Eq.3$$

2.5 Risk and uncertainty in experiments

In accordance with Knight’s (1921) definition: risk is known but uncertainty cannot be known. Thus, there are various way to incorporate risk into econometric estimations. Models of heterogeneity within choice modelling are useful as heterogeneous preferences also extends risk attitudes (Faccioli, Kuhfuss, & Czajkowski, 2019; Weber, Blais, & Betz, 2002).

Some researchers incorporate risk by specify probabilistic outcomes associated with attributes (Glenk & Colombo, 2011; Lundhede, Jacobsen, Hanley, Strange, & Thorsen, 2015). Others include it by describing it in the scenario description (Faccioli et al., 2019) or use two surveys with different outcomes, e.g. certain vs. uncertain (Roberts, Boyer, & Lusk, 2008). The treatment itself can also differ. Experimental methods distinguish between within-subject or between-subject design (Charness, Gneezy, & Kuhn, 2012). In the literature about risk in choice modelling, between-subject designs have been more common (Faccioli et al., 2019; Roberts et al., 2008; Wielgus, Gerber, Sala, & Bennett, 2009) than within-subject designs (Lundhede et al., 2015). While the majority of studies state the probabilities, some studies ask for researchers own assessment of risks (Lundhede et al., 2015).

This relates to the idea that individuals assign their own perceptions of risk and refers to an alternative model to expected utility theory, “prospect theory” (Kahneman & Tversky, 1979). Within this framework, individuals tend to undervalue outcomes that are probable compared to those that are certain. In turn, this certainty effect leads to risk aversion in probabilistic outcomes and contributes inconsistent preferences.

As discussed in this chapter, market failures commonly characterize natural and environmental resource management related to externalities and opportunity costs. In turn, these market failures can be addressed by assigning values to non-market goods. To assign values, the concept of willingness-to-pay has been proposed. Against this conceptual background, the following methods were chosen to address the research questions in this dissertation: Q-methodology, discrete choice analysis and levelized regression analysis. These methods will be described in detail in the next chapter.

3.0 Methodology

Within the dissertation, I use mixed methods and quantitative methods. Mixed methods (qualitative-quantitative) such as the Q-methodology are useful for exploratory studies and provide a theoretical basis for the subsequent studies in the dissertation. Specifically, based on the results from the Q-study, I selected attributes for a discrete choice experiment. The discrete choice experiment was selected as a means of assigning values to non-market goods. To understand economic trade-offs related to ecological hydropower mitigation and compare cost drivers, I estimated the levelized cost of mitigation and used regression analysis. The Q-methodology was used in studies 1 and 2. The discrete choice experiment was used in study 4. Levelized cost analysis and restricted maximum likelihood regression was used in study 3.

3.1 Q-methodology

The Q-methodology (henceforth Q-method) offers a structured approach and foundation to study operant subjectivity with statistical analysis (S. Brown, 1980). It is a considered a mixed method as it employs both qualitative and quantitative techniques to study stakeholder discourse in the public sphere. Due to its applied nature, it is also a useful tool for policymakers (Barry & Proops, 1999). It borrows elements from qualitative research in its development of the Q-set, which can rely on expert interviews, focus groups or case studies (Burnard, Gill, Stewart, Treasure, & Chadwick, 2008). However, while qualitative research is focused on analytical induction or grounded theory, the Q-methodology progresses further through its quantitative estimation techniques such as centroid factor analysis or principal component analysis. In this way, it ensures that subjectivity can be systematically analyzed (S. Brown, 1980). The following sub-sections will describe useful applications of the method related to renewable energy development and elements of its design.

Q-studies can be useful for identifying points of consensus and controversy related to a particular policy issue. It can be used to study public discourse and public opposition as well as improve project management and risk governance (Cuppen, Bosch-Rekveldt, Pikaar, & Mehos, 2016). Further, it is lauded as means of policy analysis, which sheds light on various positions within political debates rather than simply presenting pro and con viewpoints. In this way, it can summarize competing policy beliefs (Wolsink, 2010). It can also be used to select participants for stakeholder dialogue, which is a common means of assessing complex ecological and environmental problems (Cuppen, Breukers, Hisschemöller, & Bergsma, 2010).

For these reasons, the literature boasts a growing number of studies using the Q-methodology to understand natural resource conflict and environmental management involving a variety of stakeholders. In the sphere of renewable energy development, there are a number of studies focused on hydropower (Díaz, Adler, & Patt, 2017; Pagnussatt, Petrini, Santos, & Silveira, 2018; Venus, Hinzmann, et al., 2020). There are also a number of Q-studies examining stakeholder discourse for biomass usage (Cuppen et al., 2010), wind power (Ellis, 1998; Wolsink, 2010), photovoltaic systems (Lu, Lin, & Sun, 2018; Naspetti, Mandolesi, & Zanoli, 2016) and shale gas (Cotton, 2015; Cuppen et al., 2016). It has also been used to study relevant policy aspects of environmental infrastructure (Wolsink, 2010), transmission lines (Cotton & Devine-Wright, 2011) and river water management (Focht, 2002; Raadgever, Mostert, & Van De Giesen, 2008; Vugteveen et al., 2010). These studies primarily focus on stakeholders within one geographic region, but there are increasing examples of comparisons across regions with similar challenges including Wolsink and Breukers (2010), who contrast wind power development in northern Europe, specifically Germany, the Netherlands and the United Kingdom.

3.1.1 Design

Important elements are the Q-set (statements), P-set (respondents) and Q-sort (ranking). In this sub-section, I describe how these elements are combined within the Q-method.

The Q-set can be derived from a number of sources including scientific literature, media sources, expert interviews, focus groups and other qualitative data retrieval methods. In the first step, it is commonly recommended to use the original language (inductive) of the source (S. R. Brown, 1993). Once all of the statements have been collected, the researcher should group or code them in a iterative process. Thus, qualitative coding can be used to group similar ideas and remove repetition (Watts & Stenner, 2005). The number of statements to be included should balance trade-offs between thoroughness (i.e., covering all topics and opinions) and respondent fatigue (i.e., manageable number of statements). However, as Watts & Stenner (2005) note, a Q-set can never be complete. Thus, they argue that the main exercise is participant engagement with the Q-set. In practice, this means that participants should have the opportunity to reflect on potentially missing aspects of the Q-set in a follow-up interview. While most of the literature describes the Q-set as statements, recent applications have demonstrated that the Q-set can also be represented visually through pictures. For example, Naspetti et al (2016) conducted a visual

Q-sort to understand how perceptions of the effect of photovoltaic systems on landscape and land use.

The P-set refers to the group of participants. Compared to other methodologies, Q-studies do not require large sample sizes but rather strategically selected ones (Watts & Stenner, 2005). Many Q-studies are effective with samples of 40-60 respondents (Stainton Rogers, 1995). For this reason, large sample sizes are rare. If a large P-set is used, it is common that a share of participants do not load significantly on any factor (Carmenta, Zabala, Daeli, & Phelps, 2017; Clarke, 2002; Davies & Hodge, 2007; Milcu, Sherren, Hanspach, Abson, & Fischer, 2014). If the total explained variance is between 50-60%, it is not necessary to extract additional factors (Carmenta et al., 2017).

Within the Q-sort, pre-selected respondents (P-set) rank-order subjective statements (Q-set) according to instructions (e.g., most to least agree) with a quasi-normal distribution. While the distributional shape has no effect on statistical analysis or reliability, it is used to facilitate systematic sorting as beliefs are often characterized by extremes (S. Brown, 1993; McKeown, Stowell-Smith, & Foley, 1999). Flatter distributions can be used when the researcher expects the opinions to be stronger (Exel & Graaf, 2005). Figure 3 shows an example of a Q-sort with rankings. Within the distribution, each of the rankings corresponds to a score (e.g., most agree=+5, least agree=-5) and the scores of each individual are analyzed with centroid factor analysis or principal component analysis (PCA) (Dziopa & Ahern, 2011). As extracted factors or components represent people who have ranked the statements in a similar way, the factors or components can be conceptualized perspectives with shared attitudes (S. Brown, 1980).

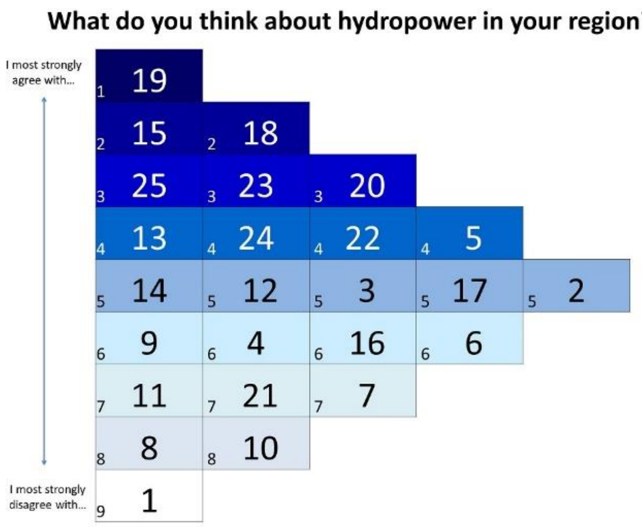

Figure 3 Example ranking of Q-set statements

Source: Venus, Hinzmann, et al., (2020) There are a variety of mediums used Q-studies, including face-to-face with visual aids and online. In face-to-face settings, participants sort paper cards with a physical grid (B. B. Walker, Lin, & McCline, 2018). Q-studies are typically conducted in three phases including an entry interview, Q-sort and exit interview. During the Q-sort, the respondent reads and sorts statements. After the respondents sort all statements, the interviewer can invite them to adjust their responses. Within the exit interview, the respondent is given the opportunity to explain their extreme answers (top three most agree and least agree statements).

The analysis is based on a by-person factor analysis, which identifies the beliefs to which different respondents subscribe (Dziopa & Ahern, 2011). After a correlation matrix of all Q-sorts is obtained, factor analysis is performed to group together respondents who have sorted the statements similarly (M. Brown, 2004). Many studies use centroid factor analysis, which is based on the sums of correlations in a factor of principal component analysis (Dziopa & Ahern, 2011). To extract factors or components, judgmental or varimax rotations can be used (McKeown et al., 1999).

Principal component analysis with varimax rotation can be applied with the *Qmethod* package in R (Zabala, 2019). The number of components to extract is based on eigenvalues, visual inspection for a discontinuity in eigenvalues with the Scree-Test, total explained variance and theoretical significance (Carmenta et al., 2017; Cattell, 1966; Watts & Stenner, 2005). To interpret the components as unique perspectives, researchers should focus on the z-scores of each statement, the extreme rankings of each component and the characteristics of respondents who loaded significantly on each component (e.g., socio-demographic characteristics, stakeholder type).

3.2 Discrete choice experiment

For non-market valuation, there are two main methods: revealed preference and stated preference based methods. Revealed preference methods include the travel cost method and hedonic pricing method. An example of the travel cost method include using recreational expenditure or travel time to estimate the value of a specific place (G. Brown & Mendelsohn, 1984). An example of the hedonic pricing method is using housing prices to isolate the effect of non-market attributes such as the proximity to an urban forest (Tyrväinen, 1997). Overall, there are limited examples of data that are suitable for this estimation. Further, hedonic pricing is limited in its ability to value future changes (Baker & Ruting, 2014).

Stated preference methods are survey-based and include contingent valuation and choice modelling. While revealed preference methods are widely accepted as valid, their applications are limited as they require a “behavioral trace” rather than measuring non-use values (Baker & Ruting, 2014). Alternatively, stated preference methods have a wider range of applicability but their validity is subject to criticism. Criticism stems from the hypothetical nature of stated preference methods, also known as hypothetical bias. Such bias may cause individuals to misstate their willingness to pay or accept different than if monetary incentives were truly at stake (Murphy, Allen, Stevens, & Weatherhead, 2005). However, there are a number of strategies used to mitigate hypothetical bias including both ex ante survey design strategies such cheap talks, certainty scales and a variety of behavioral economics methods (e.g., certainty follow-up, frequent opt-out reminders, oath treatment) as well as ex post calibration techniques (Loomis, 2014). Given the lack of suitable data for revealed preference methods and limited application to the research questions, this dissertation focuses on stated-preference methods.

3.2.1 Experimental design

The experimental design for a discrete choice experiment consists of defining the attribute and levels and choice sets. To select attributes and levels, researchers commonly orient themselves using previous literature and qualitative methods such as focus groups and expert interviews. A recent improvement has been the suggestion to use the Q-methodology to select attributes and levels (Armatas, Venn, & Watson, 2014; Jensen, 2019). Both Armatas et al (2014) and Jensen (2019) proposed the Q-methodology as a structured means of selecting attributes. Within a DCE, the attributes contribute to the validity of the non-market valuation methods. Particularly in cases of ecosystem services, it is relevant to consider different stakeholder perspectives (Armatas et al., 2014). Table 1 shows example attributes and levels for a choice experiment.

Choice set design can use the full factorial design, orthogonal design and efficient design (Hensher, Rose, & Greene, 2005; J. J. Louviere, Hensher, & Swait, 2000). As the full factorial design often results in thousands of choice combinations, researchers fuse fractional factorial designs to make the evaluation of all possible effects feasible (Auspurg & Liebe, 2011). There are different ways to reduce the number of choice tasks (e.g., random, orthogonal, efficient designs).

Table 1 Example attributes and levels in a choice experiment

Attribute	Levels
Ownership (Company)	State Private domestic Foreign
Fish Protection (Fish Pass)	No Yes
Flood Protection	Meets minimum standards Extra ecological protection
Recreation opportunities on rivers	Yes No
Increase in average monthly electricity bill	3€ 6€ 9€ 12€ 15€

Much of the literature on experimental design focuses on methods to improve estimation results by balancing asymptotic efficiency (reduction of standard errors of the estimates) with asymptotic unbiasedness (consistency of estimates) (J. L. Walker, Wang, Thorhauge, & Ben-Akiva, 2018). In orthogonal designs, the researcher identifies the main effects to estimate these parameters with precision (e.g., minimal standard errors). If all attributes are uncorrelated, the design is orthogonal. Ideally, all levels are balanced among the choice tasks (J. L. Walker et al., 2018). While orthogonal designs are widely used, they are not always the most efficient in discrete choice analysis (Kuhfeld, Tobias, & Garratt, 1994).

As a result, efficient designs emerged to minimize the standard error of the estimated model parameters via optimization based on the asymptotic variance-covariance matrix (J. L. Walker et al., 2018). They rely on prior parameter information as a best guess of the true parameters. There are several approaches to setting the priors: (i) setting all priors to zero, (ii) setting all priors to fixed, non-zero values, define the priors based on a known distribution with known parameters and (iv) updating the design during the data collection phase (Bliemer, Rose, & Hess, 2008; Sándor & Wedel, 2001, 2002). A means of selecting prior is using pilot studies (Bliemer & Collins, 2016).

Following Mitchell (2002), scenarios should be described before the respondents answered the choice tasks. As hypothetical bias can be a problem in stated preference valuation, there is no consensus on how to adjust responses for it (Murphy et al., 2005). To reduce hypothetical bias, researchers can include a cheap talk script, which describes the phenomena and requests realistic responses (Cummings & Taylor, 1999; List, Sinha, & Taylor, 2006;

Tonsor & Shupp, 2011). While cheap talks have been found to reduce hypothetical bias, they do not completely alleviate the problem (Champ, Moore, & Bishop, 2009).

There are also various mediums of choice experiments (e.g. online, in-person, mail). When comparing online and mail survey modes over six criteria (i.e., response rates, protest responses, demographics, preferences, WTP, estimation precision and choice certainty), Olsen (2009) found that some differences were observed. However, these differences did not lead to significant differences in WTP estimates, thus leading to the conclusion that the survey mode cannot invalidate the findings of different modes. While online surveys offer benefits related to reduced costs, in-person designs have been found to improve response accuracy and participation rates without leading to social desirability bias (Gallardo & Wang, 2013; Maguire, 2009; Roxas & Lindsay, 2012).

3.3 Cost analysis

Within cost analysis, the empirical study included regression models fit by restricted maximum likelihood and calculated the levelized cost of mitigation.

3.3.2 Regression models fit by restricted maximum likelihood

Restricted maximum likelihood (REML) is a form of maximum likelihood estimation. It does not base the estimates for all of the information on maximum likelihood but calculates it from a transformed set of the data (Corbeil & Searle, 1976). REML is useful for fitting linear mixed models with missing data (Calvin, 1993).

As likelihood estimation with missing data can be a difficult task and present computation problems, REML was presented as an estimation scheme for variance components matrices using an expectation maximization algorithm when the data set is unbalanced (Calvin, 1993). Unbalanced data sets can arise, for example, when data is collected from different sources.

Within this process, the expectation-maximization algorithm is important to understand. By definition, the expectation-maximization algorithm is iterative and computationally demanding. Within the E-step, the missing data values are “estimated” using the conditional distribution of the missing data given the observed data (Calvin, 1993). In the M-step, new estimates of the desired parameters are produced using the “completed” data (Calvin, 1993).

3.3.3 Levelized cost of mitigation

The levelized cost of energy (LCOE) is a widely used and accepted metric for comparing energy sources, especially for policy decisions (Aldersey-Williams & Rubert, 2019). The LCOE shows the unit cost of energy over the full life of a project. Thus, it aggregates capital, operating and financing costs over the lifetime of the energy system. Most versions of LCOE consider plant-level costs, rather than costs that may be incurred on the system level. Although it is widely used, it is often criticized in the context of renewable energy as it does not account for variability of production and cost of integrating to the grid (Ueckerdt, Hirth, Luderer, & Edenhofer, 2013).

There are two main methods used for calculating the LCOE: (i) the Department of Business, Energy and Industrial Strategy and (ii) the U.S. Department of Energy's National Renewable Energy Laboratory. The formula used by the Department of Business, Energy and Industrial Strategy is:

$$LCOE_{BEIS}=\frac{NPV_{Costs}}{NPE} = \sum_{t=1}^{n}\frac{C_t+O_t+V_t}{(1+d)^t} / \sum_{t=1}^{n}\frac{E_t}{(1+d)^t} \qquad Eq.\ 4$$

where t is the period from year 1 to year n, C_t is the capital cost in period t, O_t is the operating cost (fixed), V_t is the operating cost (variable), E_t is the energy generated, d is the discount rate and n is the last year of operation. In this formula, the discounted sum of costs is divided by the discounted sum of energy production (Aldersey-Williams & Rubert, 2019).

The U.S. Department of Energy's National Renewable Energy Laboratory has a simplified LCOE, which is defined in terms of the annual cost of energy.

$$LCOE_{NREL}=\frac{C_0+CFR+O}{8670*CF}+f*h+V \qquad Eq.\ 5$$

where C_0 is the overnight capital cost, O is the fixed operating cost, CF is the capacity factor, f is the fuel cost and h is the heat rate and V is the variable operation cost. The capacity factor is multiplied by 8670 because this is the number of hours in a year. Some technologies (e.g. hydropower) do not incur fuel costs. In turn, $LCOE_{NREL}$ shows the minimum price for electricity for an energy project to break even.

To combine the different types of costs associated with mitigation over a measure's lifetime, these formulas could be extended to estimate a levelized cost of mitigation, represented by the following formula:

$$\text{LCOM} = \frac{Sum\ of\ costs\ over\ lifetime}{Plant\ capacity} = \frac{I+\sum_{t=1}^{n}\frac{M_t+L_t}{(1+r)^t}}{C}. \qquad Eq.\ 6$$

where I is investment (construction) expenditure of the mitigation measure, M_t is maintenance expenditures in the year t, L_t is power production losses (EUR) in year t, C is plant capacity (kW), r is the discount rate, and n is the expected lifetime of the measure. Although the LCOE is usually ratio of the levelized cost of electricity divided by the discounted sum of generated electricity. As it is difficult to make assumptions about a hydropower plant's annual generation based on its capacity, plant capacity was used place of generation. Further, the assumption of full-time operation (8670 hours) is inappropriate for hydropower operation, which is subject to seasonal fluctuations. The discount rate can be selected based on recommendations from the European Commission for cost-benefit analyses (4%) which represents the time value of money (Sartori et al., 2014).

The methods described were applied in the four empirical studies of this dissertation. In the following chapter, I describe the following for each empirical study: method and main findings as well as its publication status and the authors' contributions. In studies 1 and 2, the Q-methodology was used. In study 4, I used a discrete choice experiment. In chapter 3, I estimated the levelized cost of mitigation and used regression analysis fit with restricted maximum likelihood.

4.0 Publications[1]

4.1 Understanding stakeholder preferences for future biogas development in Germany

This study investigated stakeholder preferences for the trajectory of the German biogas sector using a mix of qualitative interviews, spatial suitability analysis and a principal component analysis within the Q-methodology. While previous literature focused on identifying effects of biogas feed-in-tariffs on the agricultural sector, few studies explore the sector's outlook after the phase-out of the tariffs. Our approach is particularly unique as it focused on stakeholder preferences for the sector's trajectory and considered the implications for small-scale biogas operators. We identified four perspectives related to: (i) economic security and support, (ii) sustainability, (iii) opportunities for other farmers and (iv) alternative scale-dependent support. The discourse highlighted the tension between biogas and non-biogas farmers and focused on how to handle the supposed unequal playing field created by the feed-in-tariffs. In general, stakeholders preferred less regulation as they believed it could create perverse incentives within the agricultural sector. Specifically, there was consensus that there should not be additional feedstock rules based on regional characteristics such as nutrient-surplus or low livestock density regions. For example, while subsidies for residues storage could support biogas, they could also incentivize farmers to rear more animals, which would contradict the Fertilizer Ordinance. On the other hand, there was controversy related to long-run economic independence of biogas. Although biogas farmers believed general remuneration is essential to continue operation, non-biogas farmers questioned its equity. Despite this controversy, the results imply that tension will reduce if future support only compensates for specific aspects such as flexibility, ecological feedstock or heating.

Publication:

Venus, T. E., Strauss, F., Venus, T. J., & Sauer, J. (2021). Understanding stakeholder preferences for future biogas development in Germany. *Land Use Policy*, 109, 105704. https://doi.org/10.1016/j.landusepol.2021.105704

Authors' contribution: Terese Venus developed the research question, conceptual framework and methodology, supported data collection, conducted the formal analysis and wrote the original manuscript. Felix Strauss performed data collection and supported with data

[1] The full publications are not embedded in this dissertation to avoid plagiarism. However, the full versions were sent to the examiners for grading.

visualization. Thomas Venus supported with the methodology and the review/editing of the manuscript. Johannes Sauer provided supervisory support.

4.2 The public's perception of run-of-the-river hydropower across Europe

This study compared public values about run-of-the-river (RoR) hydropower in Germany, Portugal and Sweden. Compared to previous literature, it focused on how the type of hydropower technology (run-of-the-river) affected public views. The application of the Q-methodology was also unique in that it assessed local views with a relatively large sample size (n=148) across three major hydropower regions in Europe, specifically Scandinavia, Iberia and the Alpine region. We found significant controversy surrounding the ownership of hydropower plants and the status of hydropower as a private, common or public good. While locals were averse to foreign ownership of hydropower, there was limited consensus on the preferred type of ownership. As run-of-the-river hydropower represents potential for sustainable decentralization, the findings imply that it should be managed as distributed generation rather than as part of centralized national system similar to traditional large-scale reservoir hydropower. Further, we recommend that operators adopt win-win mitigation strategies that deliver benefits to both society and ecosystems.

Publication:

Venus, T. E., Hinzmann, M., Bakken, T. H., Gerdes, H., Godinho, F. N., Hansen, B., … Sauer, J. (2020). The public's perception of run-of-the-river hydropower across Europe. *Energy Policy*, 140, 111422. https://doi.org/10.1016/j.enpol.2020.111422

Authors' contribution: Terese Venus developed the conceptual framework and the methodology, piloted the survey and collected the final data in Germany, managed data collection in Portugal and Sweden, curated the data, analyzed the data and wrote the original manuscript. Mandy Hinzmann supported with the conceptual framework, piloting the survey and reviewing of the draft. Tor Hakken Bakken, Antonio Pinheiro and Holder Gerdes supported with the development of the conceptual framework and managed data collection. Francisco Nunes Godinho supported with data collection and visualization. Bendik Hansen supported with data collection. Johannes Sauer provided supervisory support.

4.3 Evaluating cost trade-offs between hydropower and fish passage mitigation

This study assessed trade-offs between fish passage mitigation (upstream and downstream) and hydropower production. We conducted survey with hydropower operators and literature review to collect the costs of 327 fish passages in Europe, we categorized types of costs, developed a model to predict construction costs and accounted for opportunity cost of lost power production in the lifetime costs of different passage designs under different electricity price scenarios. Recent literature has reported costs of fish passage measures with descriptive statistics but has not quantified the opportunity costs associated with lost power production. As there is limited research on the costs of fish passage measures, the findings provide a basis for including economic aspects in hydropower decision-making. Between the categories of economic and financial costs, we identified three main sub-categories of costs: capital (pre-construction, construction, management), operational (monitoring, maintenance, legal) and other (compensation for land and habitat, lost power production and lost system flexibility). When we estimated a linear mixed model fit by restricted maximum likelihood (REML), we found that the length of the pass, obstacle high, plant capacity and design (technical, nature-like or combined) were strong predictors of passage construction costs and accounted for 77% of the total variation in the data. When we compared different types of fish passage designs (i.e. technical vs. nature-like), we found that nature-like measures tend to incur lower costs, even when considering power losses. Given that nature-like solutions cost less to build and operate, incur fewer power losses and provide habitat in addition to facilitating fish passage, we demonstrate that there is a strong basis for supporting their development in Europe.

Publication:

Venus, T. E., Smialek, N., Pander, J., Harby, A., & Geist, J. (2020). Evaluating Cost Trade-Offs between Hydropower and Fish Passage Mitigation. Sustainability, 12(20), 8520. https://doi.org/10.3390/su12208520

Authors' contribution: Terese Venus developed the research question, conceptual framework and methodology as well as performed data collection and the formal analysis. Nicole Smialek supported with data collection, visualization and the conceptual framework. Joachim Pander, Atle Harby and Jürgen Geist provided supervisory support with the conceptual framework, data collection and manuscript.

4.4 Certainty pays off: the public's value of environmental monitoring

This study measured the public's value of environmental monitoring and ecological measures at hydropower plants in Bavaria, Germany. In the first step, we used the Q-methodology to select attributes for a discrete choice experiment. In the second step, we designed a split-sample choice experiment with an uncertainty treatment. While both groups were asked to make decisions about hydropower management, we provided additional information to the treatment group. We informed them that the effectiveness of one of the attributes (fish protection) was uncertain because there was no monitoring. As there has been little research on the public's value of environmental monitoring, our approach was unique and useful for both applied ecology and economics. While the value of information concept has been used in applied ecology, it is based on whether a decrease in uncertainty affects the management decision and does not incorporate public preferences. However, as the costs of monitoring are included in costs-benefit analyses, the public's value should also be accounted for in the benefits. Further, compared to previous studies on the effect of risk on environmental valuation, we use the uncertainty framework and focus on an environmental measure (fish protection) as opposed to an environmental outcome (e.g., percentage increase of fish population). This is an important distinction as the implementation of a measure signals to the consumer that it is effective in achieving its goal rather than promising an ecological outcome. We assumed heterogeneous preferences and estimated willingness to pay with the mixed logit and latent class approach. For both techniques, uncertainty significantly reduced willingness to pay by 10-33%. This demonstrates that the public positively values additional information from monitoring. Our findings have implications for decision-makers affected by environmental requirements (e.g. Water Framework Directive). Given the importance of monitoring for the public, decision-makers should ensure that monitoring is more consistent and transparent.

Publication:

Venus, T. E., & Sauer, J. (2022). Certainty pays off: The public's value of environmental monitoring. Ecological Economics, 191, 107220.
https://doi.org/10.1016/j.ecolecon.2021.107220

Authors' contribution: Terese Venus developed the research question, conceptual framework and methodology, conducted data collection, performed the formal analysis and wrote the original manuscript. Johannes Sauer provided supervisory support with the econometric analysis.

5.0 Discussion and conclusions

This dissertation aimed to value trade-offs between renewable energy development and ecosystems. Within the four studies, I assessed values, preferences, benefits and costs related to hydropower and biogas. Studies 1 and 3 focused on the producer-side while studies 2 and 4 focused on the consumer-side. In this section, I discuss the findings of the four studies as well as the two supplementary studies, limitations, future research avenues and policy implications.

5.1 Discussion of the studies

In study 1, we identified four perspectives and found a notable tension between biogas and non-biogas farmers related to idea of unequitable economic support for biogas. Such support includes general remuneration, proposed funding for building of manure storage facilities and switching to biomethane, as well as possible payments for flexible generation, ecological feedstock and waste heat cooperation. Fundamentally, the perceptions diverge as to whether biogas farmers should continue to receive economic support and privileges as non-biogas farmers argue it creates an uneven playing field within the sector in both the short and long run. In the long-run, biogas farmers (perspective 1) believe that general remuneration is required and that payments are a necessary compromise in exchange for the production of flexible, renewable energy. For small-scale biogas operators, this is particularly important as the recent amendments of the German Renewable Energy Act (EEG) are based on a tender process, which may make render them uncompetitive. On the contrary, non-biogas farmers feel that general remuneration is unequitable, particularly given that feed-in-tariffs for biogas played a role in increasing land rental prices. While non-biogas farmers also opposed support for building storage facilities, they did not strongly oppose payments for specific aspects (e.g. flexibility). While renewable energy development is often viewed independently from the agricultural sector, this study demonstrates decision-makers must consider potential impacts on the structure of German agriculture when determining biogas policies.

In study 2, the analysis reveals that ownership is a significant topic across all three regions. As run-of-the-river hydropower designs will account for a large share of future hydropower development, the technology may represent an important opportunity for sustainable decentralization and co-production. The analysis implies that compared to large-scale reservoir hydropower, run-of-the-river plants should be viewed as part of decentralized generation rather than part of a centralized national energy system. While run-of-the-river plants are often assumed to be more ecologically benign, this study revealed that locals are concerned about their ecological impact. Thus, policymakers should ensure that rigorous monitoring is conducted to measure the ecological impact of numerous plants in the same river catchment.

In study 3, we investigated drivers of the costs of fish passage mitigation. This study contributed to the literature as there is little known about costs of fish passage mitigation in Europe and previous literature has only reported descriptive statistics. In comparison, we conducted a quantitative analysis, which revealed that technical parameter account for a large share of the variability in construction costs and that construction and power losses account for a large share of lifetime mitigation costs. We also found that there was a lack of data about the costs and types of monitoring conducted. Thus, we recommended to strengthen future analysis with clear reporting of costs, structural characteristics and power losses of fish passage mitigation. Based on the costs, we also considered how mitigation should be financed and incentivized including support schemes (e.g. direct financing, grants, loans), feed-in-tariffs and green power labels. In regards to offsetting the cost of fish passage mitigation, direct financing and loans could be useful for covering construction costs while feed-in-tariffs may be promising in offsetting recurring costs stemming from power losses.

In study 4, we measured the public's value of environmental monitoring and ecological measures using a discrete choice experiment with a split-sample uncertainty treatment. This approach was unique as it allowed us to incorporate public preferences into the valuation of monitoring. The findings are relevant for policymakers as monitoring requirements are an increasingly important part of environmental regulation such as the European Union's Water Framework Directive. We recommend that monitoring and reporting is more transparent, particularly in cases when information from monitoring is used for decision-making.

This dissertation also cites three additional studies, which examine the links between climate change and smallholder vulnerability, empowerment and productivity in South Asia. Table 2 shows the studies included in this dissertation as well as the supplementary studies.

Table 2 Overview of studies in the dissertation and key findings

Title	**Main research question**	**Key findings**
a) Studies in the dissertation		
1. Understanding stakeholder preferences for future biogas development in Germany	How do stakeholders view the trajectory of the German biogas sector?	While there is disagreement on whether biogas should be economically independent in the long-run, stakeholders largely agree that economic support should be provided for specific aspects such as flexible generation, ecological feedstock and use of waste heat.
2. The public's perception of run-of-the-river hydropower across Europe	How do locals value run-of-the-river (RoR) hydropower in Germany, Portugal and Sweden?	Locals believe RoR is important for maintaining regional control, fighting climate change, promoting citizen well-being and protecting natural ecosystems. Across all three regions, strong preferences for regional ownership indicate that the technology should be managed as distributed generation rather than part of a centralized, nationalized system like large-scale reservoir hydropower.
3. Evaluating cost trade-offs between hydropower and fish passage mitigation	What are the major cost drivers of hydropower mitigation?	Technical site characteristics are significant drivers of costs. Among fish passage designs, nature-like solutions tend to incur lower costs than technical designs, even when power losses are considered.
4. Certainty pays off: the public's value of environmental monitoring	What is the public's willingness to pay for environmental mitigation and monitoring?	The public has a positive and significant willingness to pay for environmental monitoring. In our application to environmental hydropower, we find strong support for fish protection and opposition to foreign ownership.
b) Additional first-authored article cited in the dissertation		
5. Livelihood vulnerability and climate change: a comparative analysis of smallholders in the Indo-Gangetic Plains	Within the Indo-Gangetic Plains, what components contribute most to smallholder livelihood vulnerability?	In a comparative assessment of two districts, both districts have similar exposure and adaptive capacity but the sensitivity dimension makes one more vulnerable to climate change. The inclusion of self-reported climate shocks and spatially interpolated weather data can be used to reflect different aspects and improve measurements of climate exposure.
c) Additional co-authored article cited in the dissertation		
6. Measuring the Climate Dimension of Women's Empowerment in Agriculture: Comparative Evidence from Nepal	How does accounting for climate change vulnerability affect measurements of women's empowerment in agriculture in Nepal?	When a climate domain for the Abbreviated Women's Empowerment in Agriculture index is included, the climate domain is the second biggest contributor to women's disempowerment and significantly increases the number of disempowered women in both districts.

The supplementary study 5, "Livelihood vulnerability and climate change: a comparative analysis of smallholders in the Indo-Gangetic Plains" has been published in *Environment, Development and Sustainability* (Venus, Bilgram, Sauer, & Khatri-Chettri, 2021). In this study, we estimated the Livelihood Vulnerability Index in two districts (Vaishali, Bihar and Karnal, Haryana) in the Indo-Gangetic Plains, one of India's most productive agricultural regions. Within the estimation, we included both self-reported climate shocks and spatially interpolated weather to reflect different aspects of climate exposure. Both districts had similar exposure and adaptive capacity levels, but Vaishali was more sensitive to climate change. We recommended that decision-makers focus on improving infrastructure to reduce sensitivity, including permanent housing, latrines, health centers and alternative energy sources. Further, we recommended that adaptive capacity is improved through the expansion of extension training related to livelihood diversification, conservation agriculture as well as information and communication technologies.

For supplementary study 5, Terese Venus and Stefanie Bilgram developed the research question, conceptual framework, and methodology as well as prepared the data and performed the empirical analysis. Terese Venus wrote the original manuscript. Arun Khatri-Chettri collaborated with the CCAFS CGIAR Research Program on Climate Change, Agriculture and Food Security to design the original survey and collect the data in India. Johannes Sauer provided supervisory support.

The supplementary study 6, "Measuring the climate dimension of women's empowerment in agriculture: comparative studies from Nepal" is under review at *Population and Environment*. In this study, we estimated the Abbreviated Women's Empowerment in Agriculture index for two ecologically diverse regions in Nepal (Chitwan and Kaski). We also developed a unique climate dimension of the index, which consisted of three sub-indicators: awareness to climate change, access to climate-related extension services and utilization of climate mitigation and adaptation strategies. In our comparison to the original index, we found that the climate dimensions contributed the second most to disempowerment of women for both districts. Further, we found that the inclusion of climate aspects significantly increased the number of disempowered women.

Fredrick Bosche is the first author of supplementary study 6. Terese Venus, Fredrick Bosche and Maria Vrachioli developed the research question and conceptual framework. Fredrick Bosche and Terese Venus constructed the data, performed the empirical analysis and wrote the final manuscript. Arun Khatri-Chettri collaborated with the CCAFS CGIAR Research

Program on Climate Change, Agriculture and Food Security to design the original survey and collect the data in Nepal. Johannes Sauer provided supervisory support.

5.2 Limitations and recommendations for future research

There are five main limitations of this dissertation. In study 1, the study of biogas was limited by the exploratory nature of the Q-methodology. Although we were able to identify a clear tension between biogas and non-biogas farmers about the nature of biogas remuneration, we could not propose policy recommendations for resolving this tension. However, given that the research question was intended to explore stakeholder views on the trajectory of the German biogas sector, the study proposes an interesting research focus. Specifically, future quantitative research could determine the optimal and equitable level of biogas incentives for flexible generation, ecological feedstock and waste heat usage as well as conduct scenario modelling to assess how these incentives may affect the structure of agriculture (e.g. land rental prices, average farm size, etc.).

In study 2, the Q-set could have included more nuanced statements about ownership. Given that the results yielded a strong public emphasis on ownership, it would have been valuable to better analyze the diversity of views related to ownership types. However, this is one of the classic challenges of developing a Q-set and a procedural detail of the Q-methodology. As noted by Watts & Stenner (2005), "a Q set can never really be complete as there is always 'something else' that might potentially be said" (p. 75). In this sense, it is important to note that the Q-set is not the focus of the method, as it should only condense information. Instead, it is important how respondents engage with the Q-set. As a result, our qualitative analysis should have revealed any relevant views toward ownership and allowed us to explore these preferences in more detail. Based on this, future research could explore the merits of local vs. regional control as well as other types of ownership schemes including cooperatives, shareholder and single-owner co-production in different regions. Further, quantitative studies could focus on valuing different preferences related to hydropower management strategies such as ecological mitigation, different ownership types and flood control.

In study 3, a lack of information about plant generation (kWh) weakened the estimation of the levelized cost of mitigation and reduced its comparability to other studies. To remedy this limitation, we used plant capacity (kW) as a proxy of generation. While some studies calculate the yearly generation based on plant capacity, we decided against estimating generation based on capacity as run-of-the-river plants have widely varying operational hours per year. While capacity may not be the best proxy for the same reason, we believe it is a more transparent approach as detailed assumptions could overpromise precision. However, as levelized cost metrics are intended to distill comparison for policy decisions and general audiences (Aldersey-Williams & Rubert, 2019), we believe this metric is useful for comparing the costs of different fish passage mitigation designs.

Another challenge was related to the small share of the observations in the levelized cost analysis. Specifically, there were many case studies with missing information about lost power production. While some case studies stated that power losses were zero, others did not include any information. As the power losses may feasibly amount to zero, we may have overestimated the cost of lost power production. Given that energy markets change rapidly and energy demand can fluctuate at sub-daily scales, future research could focus on collecting detailed information about lost power production (e.g., time of lost power) stemming from ecological mitigation at hydropower plants. When this information is matched with electricity prices, a dynamic model could be built to estimate the true cost of lost power production. Further, it would also be interesting to investigate the economic and ecological trade-offs related environmental flow measures. As many hydropower plants adapt their production according to market demand, some countries have adopted maximum ramping rates or minimum flow rules to limit adverse effects on river ecology. However, if these limits are in place, other flexible generation sources (e.g. coal) are used to cover peak demand. Thus, it would be valuable to compare the economic and environmental impact (ecological effects in the river vs. greenhouse gas emissions) of environmental flow restrictions.

In study 4, there was potential for hypothetical bias. Many scholars criticize choice experiments and other stated preference methods for accuracy. As respondents are not required to pay real money, many are inclined to answer differently than when faced with a real market decision. While we addressed hypothetical bias through “cheap talk” script and a budget reminder, innovations from behavioral economics literature may have improved our estimates (Schmidt & Bijmolt, 2020). Examples include certainty follow-up (Whitehead & Cherry, 2007), frequent opt-out reminders (Ladenburg & Olsen, 2014) and oath treatment (Jacquemet, Joule, Luchini, & Shogren, 2013). However, we refrained from adopting these measures given the time limitations of each interview. As the core of the paper aimed to address the value of environmental monitoring, we believe the results are useful for indicating the direction of the effect (positive).

Overall, we analyzed costs of ecological hydropower mitigation in terms of construction and power losses as well as valued benefits of mitigation and monitoring. However, as these studies were conducted on different scales (e.g. Bavarian, German, European), it was not possible to conduct a cost-benefit analysis. Thus, we recommend that future research conducts a comprehensive cost-benefit analysis. For this study, an approach with several case studies would be useful given the site-specific nature of the technology.

5.3 Policy implications

The overall aim of this dissertation was to assess trade-offs between renewable energy development and ecosystems to inform decision-making, particularly in light of innovations related to mitigation measures and strategies.

In the context of hydropower and ecosystems, the results have energy policy implications. Compared to environmental flow and operational strategies (e.g. ramping restrictions), the studies in this dissertation focus primarily on fish passage mitigation. While fish passage mitigation tends to incur more costs related to construction, one should not overlook the costs they incur related to power losses. Unfortunately, our data did not indicate when these power losses occurred over daily and seasonal scales. However, the timing of losses is important for operator profitability and energy system flexibility.

In terms of profitability, research on the economics of ramping rate restrictions from hydropower has shown that restrictions may decrease profits if operators must shift production to off-peak periods when prices are lower (i.e., restrictive ramping rates), but most ramping restrictions do not significantly affect profits over a given day (Niu & Insley, 2013). Beyond the daily scale, seasonal effects could be considered in policymaking. Specifically, both ramping rate restrictions (i.e., for environmental flow) and fish passage facilities could be mandated only during specific seasons based on ecological needs. For example, fish passage facilities could operate only during fish migration to minimize power losses (Romão, Santos, Katopodis, Pinheiro, & Branco, 2018).

Concerns with profitability also relate to the costs of planning, constructing and monitoring measures. Although standardization of mitigation may be tempting to reduce costs overall, standardized fish passages not be effective (Birnie-Gauvin, Franklin, Wilkes, & Aarestrup, 2019). However, while most mitigation is negotiated within license renewal agreements (in Germany), site-specific measures must also be balanced with sufficient monitoring and reporting to increase transparency. This is especially important as our research revealed that there is significant demand but limited monitoring.

This research also has implications related to compensation for ecological mitigation, payments for ecosystem services and incentives for effective mitigation. Examples of financing instruments include direct financing, grants, loans, feed-in-tariffs and green power labels (Kampa et al., 2017). In some countries, state authorities finance ecological mitigation using taxes (e.g., Switzerland, Austria) whereas others incentivize ecological mitigation through labelling (e.g., Sweden). As targeted financial support may foster mitigation at sites with the greatest ecological need, this financing approach may maximize effectiveness. Effective ecological mitigation may also be incentivized through results-based payment schemes. In the context of agricultural pollution abatement, results-based payments may have lower adoption rates, but result in more effective abatement measures (Sidemo-Holm, Smith, & Brady, 2018). Similarly, results-based payments for mitigation could use indicator species or other proxies of good ecological status to determine payments.

In terms of system flexibility, one of the major challenges of a renewable energy transition at the German and European levels is the mismatched supply and demand of energy over space and time. While most energy storage technologies are still in the nascent phases, hydropower offers the best solution for large-scale energy storage within the renewable energy transition as other ramping (or peaking) plants tend to be conventional gas or coal fired plants. We recommend that ecological mitigation for hydropower is site-specific and context-specific, considering at plant, market and catchment conditions. Given efforts to expand renewable capacity through small-scale hydropower (BMU, 2010), it is important to remember that plant size (capacity) is not a reliable indicator for ecological impact relative to generation (Bakken et al., 2012). As many plants along the same watercourse may have a cumulatively higher impact (D. Anderson et al., 2015), planning and mitigation must be performed on a catchment level. Further, if new hydropower plants are built, they should be built in areas where they will have as minimal an impact on ecosystems as possible to reduce negative externalities. Additionally, this research highlights the need to value lost flexibility for both the operator and the system as a whole when considering mitigation trade-offs. On the demand-side, there has been significant research focused on incentivizing energy consumers to shift their consumption from peak-periods to off-peak periods (e.g., smart tariffs). However, research on the producer-side to produce flexibly has been limited to studies of prosumer preferences for different power supply contracts (Kubli, Loock, & Wüstenhagen, 2018).

In the context of biogas and ecosystems, we focused on stakeholder views on the preferred trajectory of the sector. Based on the controversy related to the economic independence of biogas, we recommend that support mainly focuses on specific aspects of biogas rather than remuneration from feed-in-tariffs. This aligns with the current policy status as feed-in-tariffs for biogas as being phased out and replaced with a competitive tender process.

As the role of heating was less controversial, we recommend that policymakers focus on supporting efforts to link communities and biogas plants with heating concepts and other cooperation potential. For example, some states have created an online map showing sources of industrial waste heat, which enables project planners to identify sources and strengths of waste heat and build accordingly. This idea could be directly integrated into the existing Energie Atlas Bayern online map (Bayerisches Landesamt für Umwelt, 2020), which shows the location of all biogas plants in Bavaria. Additional information could be included to show whether biogas plants have potential to share their waste heat and whether there is potential for cooperation among farmers on biogas concepts.

In terms of substrate management, strong stakeholder support for ecological feedstock that fosters biodiversity (e.g., Silphium perfoliatum) indicates that policymakers could explore opportunities to provide farmers with bonus payments to incentivize their cultivation or payments for ecosystems services within results-based schemes.

For manure-based plants, policymakers should explore the potential for greenhouse gas emissions certificates (RED II certification), in which operators are compensated for reducing existing greenhouse gas emissions. Given the emissions that would have been produced through manure storage, biogas offers an alternative. In turn, operators may have the possibility to sell their certificates, which creates an additional value income stream for manure-based biogas plants. Additionally, we recommend that policymakers consider a variety of alternative support mechanisms for small biogas plants including collaborative models, private incentives for cooperation and payments for additional services that biogas plants offer to society including heating, drying of grains/woods and the reduction of greenhouse gas emissions.

Overall, this dissertation highlights that while renewable energy development is often viewed positively, its development must adopt a systems approach and consider its holistic environmental and socio-economic impact.

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