UFZ HELMHOLTZ
Centre for Environmental Research

UFZ Discussion Papers

Department of Economics

1/2021

Managing the Spatial Externalities of Renewable Energy Deployment: Uniform vs. Differentiated Regulation

Charlotte Geiger, Paul Lehmann

March 2021

Publisher:
Helmholtz-Zentrum für Umweltforschung GmbH – UFZ
Permoserstr. 15
04318 Leipzig

ISSN 1436-140X

Managing the Spatial Externalities of Renewable Energy Deployment: Uniform vs. Differentiated Regulation

Charlotte Geiger*[a,b] and Paul Lehmann†[a,b]

[a]University of Leipzig, Faculty of Economics and Management Science, Institute for Infrastructure and Resources Management, Research Group MultiplEE, Ritterstr. 12, 04109 Lepzig, Germany
[b]Helmholtz-Centre for Environmental Research – UFZ, Department of Economics, Permoserstr. 15, 04318 Leipzig, Germany

Abstract

With the expansion of renewable energy sources (RES) in countries all over the world, policy design to address the negative impacts of RES plants on their local and regional environment gains in importance. We analyse whether policy design should be spatially-differentiated or uniform when negative RES environmental externalities are spatially heterogeneous and display interregional cumulative effects. In a theoretical model of the RES electricity generation sector, we compare the welfare differential between both regulatory designs and analyse how it is affected by cumulative environmental effects. While we confirm that the welfare costs of attaining a RES deployment target are lower under a spatially-differentiated than a spatially-uniform regulation, we find that the welfare costs are contingent on the presence of cumulative environmental effects. This depends on the heterogeneity of region-specific generation cost parameters and social cost parameters of RES electricity generation. If heterogeneity is more (less) pronounced in regional generation cost parameters than in regional social cost parameters, positive (negative) cumulative effects decrease the welfare costs of a uniform instrument.

Keywords: environmental regulation, renewable energy subsidies, regional environmental damages, interregional environmental damages, renewable energy deployment
JEL classification: D61, D62, H21, H23, Q48, Q58

*Corresponding author: geiger@wifa.uni-leipzig.de
†lehmann@wifa.uni-leipzig.de

The current work has been funded by the German Federal Ministry of Education and Research under Grant 01UU1703.

1 Introduction

Fostering renewable energy sources (RES) for electricity generation has been one of the crucial steps of governments all over the world to address the problem of climate change. By reducing CO_2 emissions in the power sector, RES are known as sustainable alternative for electricity generation as compared to conventional electricity generation technologies (Evans et al., 2009; Sims et al., 2003). However, at a local or regional scale, RES also exhibit negative effects on the environment (Zerrahn, 2017; Dai et al., 2015; Tsoutsos et al., 2005). The occurrence and extent of these externalities are spatially heterogeneous, i.e. highly dependant on local and regional characteristics of generation sites. For example, wind power plants onshore are frequently associated with a decline in scenic beauty or with negative effects on wind power sensitive bird and bat species (Zerrahn, 2017; Mattmann et al., 2016). Yet, the actual level of intrusion depends on landscape characteristics or the type of bird and bat habitats (Molnarova et al., 2012; Hötker et al., 2006; Drewitt and Langston, 2006). From an interregional perspective, RES generation in several regions can additionally cause cumulative effects on the environment. Marginal environmental damages of RES electricity generation in one region then also depend on RES electricity generation in another region. For example, the regional disturbance caused by wind turbines to bird populations depends on both, the type of habitat the plants are sited in and the availability of alternative habitat in adjacent regions (Drewitt and Langston, 2006). If birds can migrate to alternative habitats, they may avoid the disturbance caused by wind turbines in their original habitat. This option does not exist if alternative habitats are also disturbed by wind turbines (Gill et al., 2001). Thus, marginal damages of installing wind power plants in one habitat depend on whether turbines are also installed in alternative habitats. Another example for cumulative environmental effects with respect to RES deployment is the presence of fairness preferences, which account for the fact that people might resist inequitable outcomes of allocation processes (Fehr and Schmidt, 1999; Fehr et al., 2006). In the context of RES deployment, fairness preferences at a spatial scale capture the fact that how strongly residents perceive negative effects of wind turbines on e.g. scenic beauty in their region may also depend on how evenly wind turbines and the related environmental damages are distributed across regions (Lehmann et al., 2020; Drechsler et al., 2017; Langer et al., 2016).

Consequently, managing the negative environmental effects of RES deployment entails two regulatory challenges that emerge from the externality characteristics of spatial heterogeneity and cumulative effects on the environment. In this paper, we analyse how these two characteristics may affect the optimal design of policies to support RES deployment. While RES support policies usually vary between RES technologies, technology-specific policies are mostly uniform. Exceptions include variations according to spatial differences in solar and wind resources or power system costs (del Río, 2017). However, payment schemes mostly do not account for location-specific environmental externalities. In Germany, for example, support payments for larger RES projects are defined in national auctions. Payments are mostly differentiated according to production technologies, such as wind onshore and offshore, solar PV and biomass. Spatially varying components are considered with respect to wind yield or the geographical location of plants in the northern or southern regions of Germany (EEG 2021). The inclusion of spatially-heterogeneous environmental costs in the price signal for further RES expansion may hold significant potential for welfare improvements. Yet, it may also be associated with higher transaction costs of policy design (Lehmann, 2013).

Against this background, we analyse the performance of spatially-differentiated and spatially-uniform policy designs for the regulation of RES expansion in the presence of complex spatial externalities. We apply a theoretical partial equilibrium model of the RES electricity sector and compare the welfare outcomes of a spatially-differentiated and a uniform subsidy. We aim at understanding the size of potential welfare differences and at identifying the parameters that may drive these differences.

Standard insights from spatial environmental economics suggest that, under perfect information, spatially differentiated policies are always preferable over uniform instruments to regulate site-specific environmental externalities (Tietenberg, 1978; Kolstad, 1987). Tietenberg (1978, 1995) argues that spatially differentiated emission charges reach air pollution targets from non-uniformly mixed pollutants at lowest cost, while their uniform counterpart is accompanied by a significant welfare loss. Kolstad (1987) finds that the welfare loss of regulating a spatially heterogeneous pollutant with a uniform instrument is growing in the steepness of marginal benefit and cost functions. In a more recent study, Fowlie and Muller (2019) argue that this rule for optimal policy design may be challenged in a second-best setting with informational constraints. They show that a spatially-uniform emission trading scheme ex post dominates a spatially-differentiated trading design in terms of welfare if the policy maker sufficiently underestimates firm's spatially heterogeneous abatement costs ex ante. However, from an ex ante perspective, the dominance of the spatially-differentiated regulation is unaltered.

Yet, these studies do not analyse how cumulative effects on the environment may affect this policy evaluation. The literature on the regulation of cumulative effects mainly deals with the interaction of pollutants in abatement costs or environmental damages. Respective findings suggest that optimal and second-best policy design depend on both, the type of interaction, i.e. whether pollutants are complements or substitutes in abatement cost (Stranlund and Son, 2019; Crago and Stranlund, 2015; Ambec and Coria, 2013; Caplan, 2006; Moslener and Requate, 2007) or environmental damage production (Ambec and Coria, 2013), and on the level of interaction. However, the simultaneous existence of cumulative effects and spatially varying environmental externalities is not examined in these contributions.

To our knowledge, the only paper so far which extends the analysis to environmental damages that display both spatial heterogeneity and cumulative effects is the study of payments for biodiversity-enhancing land-use measures by Waetzold and Drechsler (2005). For the comparison of spatially-differing and uniform payments, they model cumulative environmental benefits as the product of regional environmental benefits from biodiversity-enhancing land-use measures. Their results support the finding that uniform instrument design may bring about substantial welfare losses as compared to differentiated policies. Further, Waetzold and Drechsler (2005) show that, when cumulative benefits are taken into account, the welfare losses of uniform instruments are lowest if costs and benefits are correlated negatively across regions.

In contrast to Waetzold and Drechsler (2005), we consider cumulative environmental effects as an additional component to aggregate environmental damages. We thereby include both environmental externalities from regional and interregional RES deployment. Furthermore, we allow for cumulative effects to either increase or decrease aggregate environmental damages. Our findings show that spatially differentiated instruments continue to welfare-dominate spatially uniform regulations if environmental externalities vary at a spatial level and cumulative environmental effects occur. Further, we find that the impact of cumulative environmental effects on the welfare costs of a uniform regulation primarily depends on the heterogeneity of region-specific generation cost and social cost parameters and on the size and direction of cumulative effects. We define region-specific social cost parameters as the sum of regional generation cost and environmental damage parameters. If the heterogeneity in generation cost parameters is stronger than in social cost parameters, negative cumulative environmental effects increase the welfare differential between a spatially-differentiated and uniform instrument. However, positive cumulative effects may reduce the welfare differential, if they are not too strong. It is therefore necessary to consider cumulative effects for policy design choices. While spatially-differentiated instruments result in the socially-optimal spatial allocation of electricity generation, they are also associated with high transaction costs (Lehmann, 2012; Coggan et al., 2010). Therefore, the welfare gains of spatially-differentiating instrument design, i.e. the welfare differential between spatially-differentiated and uniform instruments, may vanish, when transaction costs are also taken into account.

The paper is organised as follows. In Section 2, we introduce the theoretical model and the policy options we subsequently analyse. In Section 3, we show the socially optimal spatial allocation of electricity generation. In Section 4, we derive the spatial allocation of electricity generation for the different policy designs and analyse the corresponding welfare costs as well as the welfare differential. In Section 5, the theoretical model is calibrated for an empirical example. In Section 6, we discuss our findings and conclude in the final section of the paper.

2 Model

Our model represents the RES sub-sector of the electricity generation market. We thereby abstract from any non-renewable sources for electricity generation. A regulator seeks to attain an external RES electricity generation target by implementing a subsidy for electricity generated by renewable energies. Given the subsidy level, a private investor decides on electricity generation. RES deployment can take place in two regions and is associated with two types of costs: generation costs that accrue during the process of electricity generation and environmental damages that occur as negative externalities of the generation process.

2.1 Generation costs and environmental externalities

Electricity generation costs vary between the two regions i and j:

$$C_i(x_i) = \frac{c_i}{2}{x_i}^2, \qquad \text{with} \qquad c_i > 0 \tag{1}$$

where $C_j(x_j)$ is analogous except that $c_j > 0$ is larger or smaller than c_i. Region-specific costs are increasing and convex in regional electricity generation x_i and x_j, respectively. Convexity of region-specific costs is based on the heterogeneity of plant site quality *within* a region. To enhance regional RES electricity generation, it is necessary to increase the number of power plants. Since the quality of potential plant sites within a region varies depending on natural conditions for RES electricity generation, such as wind yield or solar radiation, additional power plants are sited at locations with increasingly less favourable natural conditions. Fixed generation costs per plant, such as investment, installation, operating and maintenance costs (Kost et al., 2018; Ueckerdt et al., 2013), are then allocated across lower levels of average electricity generation per plant. Thus, in our model, region-specific marginal generation costs linearly increase with the factor c_i or c_j. Naturally, physical conditions for electricity yield may also significantly vary *between* regions. Therefore, c_i varies across regions, manifesting the spatial heterogeneity of generation costs, $c_i \neq c_j$ (Kost et al., 2018; Borenstein, 2012).

The second type of costs caused by RES electricity generation are negative environmental externalities. We assume a simplified environmental damage function that is composed of additively connected spatial features:

$$D(x_i, x_j) = \frac{d_i}{2}{x_i}^2 + \frac{d_j}{2}{x_j}^2 + kx_ix_j \qquad \text{with} \quad d_i, d_j > 0, \quad d_i \neq d_j, \quad k \neq 0, \tag{2}$$

The first and second term in equation (2) represent environmental damages that arise due to region-specific electricity generation x_i in region i and x_j in region j, respectively. Similar to generation costs, environmental damages from region-specific electricity generation depend on spatial characteristics that vary across regions. For example, wind turbines onshore may harm regional bird or bat species that are sensitive to power plants. The turbines can pose a risk of collision for individual animals or cause displacement effects that potentially result in habitat loss (Drewitt and Langston, 2006). The severity of these effects varies with specifications of other local or regional factors, such as distance to the aerie or habitat use and habitat quality (Schuster et al., 2015; Hötker et al., 2006; Drewitt and Langston, 2006). Similarly, large scale PV systems and onshore wind power plants can negatively affect the quality of their surrounding landscape (Botelho et al., 2017; Meyerhoff et al., 2010). The extent of this effect depends on regional landscape features such as elevation or the level of scenic quality. E.g., Molnarova et al. (2012) find that siting wind turbines in mountainous regions with many natural elements has a higher negative effect on scenic beauty than in lowland agricultural areas. In our model, the level of spatial heterogeneity in environmental damages is captured by diverging regional damage parameters d_i and d_j.

The third term in equation (2) comprises cumulative environmental effects of electricity generation that emerge if generation takes place in more than one region. This captures the fact that marginal environmental damages from electricity generation in region i depend on electricity generation in region j, $\frac{\partial D}{\partial x_i} = d_ix_i + kx_j$, and vice versa. The corresponding cross-derivative is thus equal to the cumulative impact factor, $\frac{\partial^2 D}{\partial x_i \partial x_j} = k$.

If cumulative effects are positive, expressed by $k > 0$, aggregate environmental damages increase if electricity is generated in *both* regions. On the contrary, negative cumulative effects, expressed by $k < 0$, decrease aggregate environmental damages if RES electricity generation takes place in *both* regions. Thus, aggregate environmental damages are increased by positive cumulative effects and decreased by negative cumulative effects. For both options there are empirical examples that depend on the environmental externality of interest.

For example, the impact of onshore wind turbines on regional bird populations not only depends on regional factors, such as habitat quality, but also on the availability of suitable alternative habitat in adjacent regions. If birds are disturbed by wind power developments in their habitat, they may migrate to alternative suitable habitats. However, if wind power development takes place in these habitats as well, this option can be lost. The birds may then need to remain in their original habitat and face reduced survival probabilities or diminishing reproductive success (Drewitt and Langston, 2006; Gill et al., 2001). In our model, this would be depicted by $k > 0$, indicating positive cumulative environmental effects.

A second example is the impact of wind turbines on landscape quality. In this context, cumulative environmental effects may arise due to fairness preferences at a spatial scale (Fehr and Schmidt, 1999; Fehr et al., 2006). That is, preferences regarding the spatially even or uneven deployment of wind power plants (Sasse and Trutnevyte, 2019; Jenkins et al., 2016). If a spatially more balanced allocation of wind turbines is favoured (Lehmann et al., 2020; Drechsler et al., 2017; Langer et al., 2016), deploying wind turbines in more than one region reduces aggregate damages from wind power plants to the landscape. That is, people perceive wind power plants as less harmful to scenery if damages to the landscape are distributed across regions. In this example, cumulative environmental effects are negative, expressed by $k < 0$.

2.2 Policy Options

The regulator is assumed to be benevolent and perfectly informed about both generation costs and environmental damages associated with RES electricity generation. The regulator pursues the exogenous supraregional RES electricity generation target $\bar{X}$. This is a popular measure by governments to promote RES development, mostly in terms of quantity or percentage targets (IRENA, 2020). We further assume that regional electricity generation x_i, x_j is perfectly substitutable in reaching the generation target:

$$x_i + x_j \geq \bar{X}, \quad \text{with} \quad 0 \leq x_i, x_j \quad \text{and} \quad \bar{X} > 0$$

The actual level of regional electricity generation is determined by a private investor who maximises interregional profits. To incentivize private investment in RES electricity generation, the regulator implements a per-unit subsidy s for electricity generated by renewable sources. The subsidy may either be spatially-differentiated ($s_i \; = s_j$) or spatially-uniform ($s_i = s_j = s$). The welfare outcomes of both regulatory designs are compared and the corresponding welfare differential is analysed with a focus on the impact of cumulative environmental effects.

3 Social optimum

Before the regulation schemes are examined, we first determine the efficient spatial allocation of electricity generation. In the social optimum, RES electricity generation is allocated across regions such that the social costs of reaching the generation target $\bar{X}$ are minimised:

$$\min_{x_i, x_j} SC = C_i(x_i) + C_j(x_j) + D(x_i, x_j) \qquad \text{s.t.} \qquad x_i + x_j \geq \bar{X}, \qquad x_i \geq 0 \tag{3}$$

The problem is solved by forming the Lagrangian of (3) and taking the derivates with respect to x_i, x_j and the Lagrange multiplier λ (see Appendix A). The corresponding first-order conditions for an inner solution call for equating marginal costs of electricity generation across regions:

$$(c_i + d_i)x_i + kx_j = (c_j + d_j)x_j + kx_i$$

Inserting the quantity constraint for $\bar{X}$ reaches the socially optimal allocation x_i^*, x_j^*:

$$x_i^* = \frac{\bar{X}(c_j + d_j - k)}{c_i + d_i + c_j + d_j - 2k}, \qquad x_j^* = \frac{\bar{X}(c_i + d_i - k)}{c_i + d_i + c_j + d_j - 2k}, \tag{4}$$

The solution x_i^*, x_j^* only represents the minimum of the social cost function if cumulative environmental effects are lower than $\alpha = \frac{c_i+d_i+c_j+d_j}{2}$ (refer to Appendix A for the corresponding bordered Hessian matrix). Otherwise, that is if $k > \alpha$, the social cost function is concave and x_i^*, x_j^* indicates the maximum of social electricity generation costs. In this case, it is optimal to implement a corner solution. Electricity generation then exclusively takes place in the region with lower generation cost and environmental damage parameters. Therefore, cumulative environmental effects do not emerge at the social optimum in this case. Similarly, cumulative environmental effects from electricity generation do not emerge if a corner solution is optimal and social costs are convex, i.e. if $k < \alpha$. This is the case if the level of cumulative effects k is higher than the sum of region-specific generation cost and environmental damage parameters in either region. Then, optimal electricity generation in the region with higher generation cost and environmental damage parameters would be negative for an inner solution (4). Since this is not possible, a corner solution in the region with lower generation cost and environmental damage parameters is optimal.

For an inner solution, it follows from (4) that first-best generation levels x_i^*, x_j^* are higher (lower) in the region with lower (higher) region-specific generation cost and environmental damage parameters, $(c_i + d_i), (c_j + d_j)$. The difference in optimal regional generation levels is higher if the heterogeneity in region-specific cost parameters $(c_i + d_i), (c_j + d_j)$ is more pronounced. The impact of cumulative environmental effects on x_i^*, x_j^* depends on region-specific cost and damage parameters $(c_i + d_i), (c_j + d_j)$ as well:

$$\frac{\partial x_i^*}{\partial k} = \frac{\bar{X}(c_j + d_j - c_i - d_i)}{(c_i + d_i + c_j + d_j - 2k)^2}, \qquad \frac{\partial x_j^*}{\partial k} = \frac{\bar{X}(c_i + d_i - c_j - d_j)}{(c_i + d_i + c_j + d_j - 2k)^2} \tag{5}$$

Increasing (decreasing) cumulative environmental effects raise electricity generation in the region with lower (higher) cost and damage parameters. Considering the sign of k this implies that when a positive cumulative effect, $k > 0$, grows stronger, generation levels are shifted from the region with higher cost and damage parameters to the region with lower cost and damage parameters in the social optimum. On the contrary, if a negative cumulative impact, $k < 0$, grows stronger (i.e. if it decreases in mathematical terms), the opposite is true. Furthermore, in the optimum, which region generates a higher share of the target $\bar{X}$ is determined by the spatial distribution of generation cost and damage parameters, independent of cumulative environmental effects k:

$$x_i^* - x_j^* = \Delta x^* = \frac{(c_j + d_j - c_i - d_i)\bar{X}}{c_i + d_i + c_j + d_j - 2k} \gtrless 0 \qquad \text{for} \qquad c_j + d_j \gtrless c_i + d_i$$

Depending on the difference between generation cost and damage parameters across regions, the sign of Δx^* is either positive or negative. However, for the assumption of convex social costs ($k < \alpha$), it is independent of the cumulative effect k. Thus, cumulative environmental effects can strengthen or weaken regional generation cost and damage advantages, but can never offset them.

The minimal social costs of reaching $\bar{X}$ are derived by inserting first-best regional generation levels x_i^*, x_j^* (4) into the social cost function (3):

$$SC^*(c_i, c_j, d_i, d_j, k, \bar{X}) = \frac{\bar{X}^2}{2} \frac{(c_i + d_i)(c_j + d_j) - k^2}{(c_i + d_i + c_j + d_j - 2k)}, \tag{6}$$

4 Policy Scenarios

To analyse the efficiency of a spatially-differentiated and a spatially-uniform instrument, we derive the welfare outcomes of both regulatory designs and subsequently compare them.

4.1 Spatially-differentiated subsidy

If the regulator implements a spatially-differentiated subsidy to incentivise electricity generation from renewable resources, total subsidy payments to the private investor depend on the spatial allocation of electricity generation across regions. Within each region, the subsidy s_i, s_j is uniform. The private investor's profits from RES electricity generation are represented by total subsidy payments net of total generation costs. Profits are maximised with respect to region-specific electricity generation x_i, x_j:

$$\max_{x_i, x_j} \pi = s_i x_i + s_j x_j - C_i(x_i) - C_j(x_j)$$

This yields the following first-order conditions:

$$x_i c_i = s_i, \qquad\qquad x_j c_j = s_j$$
$$x_i = \frac{s_i}{c_i}, \qquad\qquad x_j = \frac{s_j}{c_j} \tag{7}$$

The investor produces renewable electricity in each region until marginal generation costs equal the regional per-unit subsidy s_i, s_j.

The socially optimal spatially-differentiated subsidy is derived by inserting the private investor's first-order conditions (7) into the social cost function (4) and by minimizing with respect to s_i, s_j:

$$\min_{s_i,s_j} SC = \frac{c_i}{2}\left(\frac{s_i}{c_i}\right)^2 + \frac{c_j}{2}\left(\frac{s_j}{c_j}\right)^2 + \frac{d_i}{2}\left(\frac{s_i}{c_i}\right)^2 + \frac{d_j}{2}\left(\frac{s_j}{c_j}\right)^2 + k\left(\frac{s_i}{c_i}\right)\left(\frac{s_j}{c_j}\right) \quad s.t. \quad \left(\frac{s_i}{c_i}\right) + \left(\frac{s_j}{c_j}\right) \geq \bar{X}$$
$$\frac{s_i}{c_i}, \frac{s_j}{c_j} \geq 0$$

Solving for the first-best spatially-differentiated subsidies s_i^*, s_j^* reaches:

$$s_i^* = \frac{\bar{X}c_i(c_j + d_j - k)}{(c_i + d_i + c_j + d_j - 2k)}, \qquad s_j^* = \frac{\bar{X}c_j(c_i + d_i - k)}{(c_i + d_i + c_j + d_j - 2k)} \tag{8}$$

In the optimum, the subsidy is higher (lower) in the region with the lower (higher) total of generation cost and environmental damage parameters. Cumulative environmental effects influence the socially-optimal subsidy levels depending on the spatial distribution of generation cost and environmental damage parameters:

$$\frac{\partial s_i^*}{\partial k} = \frac{c_i(c_j + d_j - c_i - d_i)\bar{X}}{(c_i + d_i + c_j + d_j - 2k)^2}, \qquad \frac{\partial s_j^*}{\partial k} = \frac{c_j(c_i + d_i - c_j - d_j)\bar{X}}{(c_i + d_i + c_j + d_j - 2k)^2}$$

The first-best subsidy level is increased (reduced) by increasing positive cumulative environmental effects, $\partial k > 0$, in the region with a lower (higher) total of generation cost and damage parameters, $(c_i + d_i), (c_j + d_j)$. On the contrary, increasingly negative cumulative environmental effects, $\partial k < 0$, decrease (increase) the socially optimal subsidy in the region with a lower (higher) total of generation cost and damage parameters.
Inserting optimal spatially-differentiated subsidies (8) into the private investor's first-order conditions (7) shows that the first-best allocation of electricity generation across regions (4) is implemented. Therefore, the social costs of a spatially-differentiated subsidy are minimal and equal to the socially optimal level SC^* (6).

4.2 Spatially-uniform subsidy

Instead of spatially-differentiating subsidy design, the regulator may implement a uniform subsidy for RES electricity generation that is equal across regions. Even though, as demonstrated above, spatially-differentiated subsidies achieve the efficient outcome, high administrative costs of differentiated regulation or legal restricitons may turn this instrument infeasible.
With a uniform subsidy, the private investor's optimization problem changes to:

$$\max_{x_i,x_j} \pi = s(x_i + x_j) - C_i(x_i) - C_j(x_j),$$

The respective first-order conditions are as follows:

$$x_i c_i = s, \qquad x_j c_j = s$$
$$x_i = \frac{s}{c_i}, \qquad x_j = \frac{s}{c_j} \tag{9}$$

With a uniform subsidy, the private investor increases regional electricity generation until marginal generation costs are equal across regions and correspond to the subsid s. Therefore, x_i, x_j in (9) represents the generation-cost-minimal spatial allocation of electricity generation.

At this point, regional generation matches the ratio between the uniform subsidy and the region-specific generation cost parameter.

The level of the uniform subsidy is derived by inserting x_i, x_j from (9) into the quantity target restriction and by subsequently solving for s:

$$\bar{X} = x_i + x_j = \frac{s}{c_i} + \frac{s}{c_j}$$

$$s^U = \frac{c_i c_j \bar{X}}{c_i + c_j} \tag{10}$$

Substituting the subsidy s^U into the investor's first-order condition (9) reaches region-specific electricity generation x_i^U, x_j^U:

$$x_i^U = \frac{c_j \bar{X}}{c_i + c_j}, \qquad x_j^U = \frac{c_i \bar{X}}{c_i + c_j} \tag{11}$$

For a uniform regulation, regional electricity generation is only contingent on regional marginal generation costs as well as the target $\bar{X}$. Thus, the regulator neglects environmental damages entirely to focus on reaching the generation target $\bar{X}$ (10). The share of $\bar{X}$ generated in region i, j is based on the ratio between the generation cost parameter c_j, c_i and the sum of generation cost parameters in both regions $c_i + c_j$. Electricity generation is higher (lower) in the region with the lower (higher) generation cost parameter.

Total social costs of reaching the electricity generation target with a uniform subsidy are derived by inserting x_i^U, x_j^U (11) into the social cost function (3):

$$SC^U(c_i, c_j, d_i, d_j, k, \bar{X}) = \frac{\bar{X}^2}{2} \frac{c_i^2 c_j + c_i c_j^2 + c_i^2 d_j + c_j^2 d_i + 2k c_i c_j}{(c_i + c_j)^2} \tag{12}$$

4.3 Welfare differential: spatially-differentiated vs. spatially-uniform subsidy

The welfare difference between a spatially-differentiated and a uniform regulation is derived by subtracting the social costs of a spatially-differentiated subsidy, which are equal to minimal social costs (6), from the social costs of a uniform subsidy (12):

$$\begin{aligned} \Delta SC = SC^U - SC^* = \\ = \frac{\bar{X}^2}{2} \frac{c_i^2 c_j + c_i c_j^2 + c_i^2 d_j + c_j^2 d_i + 2k c_i c_j}{(c_i + c_j)^2} - \frac{\bar{X}^2}{2} \frac{(c_i + d_i)(c_j + d_j) - k^2}{(c_i + d_i + c_j + d_j - 2k)} = \\ = \frac{\bar{X}^2}{2} \frac{(c_i(d_j - k) - c_j(d_i - k))^2}{(c_i + c_j)^2 (c_i + d_i + c_j + d_j - 2k)}, \end{aligned} \tag{13}$$

$$\Delta SC = 0 \qquad \Rightarrow k = \frac{c_i d_j - c_j d_i}{c_i - c_j} = k_A \tag{14}$$

For the assumption of convex social costs (i.e. $k < \alpha$), the welfare differential is always greater than or equal to zero. The latter is true if cumulative effects are equal to k_A (14). In this case, a spatially-uniform subsidy is efficient, such that regional electricity generation is identical for the two regulatory designs:

$$\text{for} \quad k = k_A = \frac{c_i d_j - c_j d_i}{c_i - c_j} \qquad \Rightarrow s_i^* = s_j^* = s^U = \frac{c_i c_j \bar{X}}{(c_i + c_j)} \qquad \Rightarrow x_i^* = x_i^U, \quad x_j^* = x_j^U$$

Therefore, governing RES deployment with a uniform instrument is always more costly than – or as costly as – with a spatially-differentiated policy. This basic result confirms the findings of the literature: it remains efficient to manage spatially-heterogeneous environmental effects with spatially-differentiated policies even in the presence of interregional cumulative environmental effects.

However, the existence of the cumulative effect k on the environment may reduce or enhance the welfare differential ΔSC[1]:

$$\frac{\partial \Delta SC}{\partial k} = \underbrace{-\frac{k\bar{X}^2(c_i+d_i-c_j-d_j)^2}{c_i+d_i+c_j+d_j-2k)^3} + \frac{k\bar{X}^2(c_i+d_i-c_j-d_j)^2}{c_i+d_i+c_j+d_j-2k)^3}}_{=0} +$$

$$+ \underbrace{\frac{c_i c_j \bar{X}^2}{(c_i+c_j)^2} - \frac{\bar{X}^2(c_i+d_i-k)(c_j+d_j-k)}{(c_i+d_i+c_j+d_j-2k)^2}}_{=x_i^U x_j^U - x_i^* x_j^*}$$

$$\frac{\partial \Delta SC}{\partial k} = \underbrace{\frac{(c_i(c_i+d_i-k)-c_j(c_j+d_j-k))(c_j(d_i-k)-c_i(d_j-k))}{(c_i+c_j)^2(c_i+d_i+c_j+d_j-2k)^2}}_{=x_i^U x_j^U - x_i^* x_j^*} \gtreqless 0 \qquad (15)$$

The marginal impact of cumulative environmental effects on the welfare differential between a spatially-differentiated and a uniform regulation depends on how the difference between the terms $x_i^* x_j^*$ and $x_i^U x_j^U$ is altered. These terms can be interpreted as measures for the *spatial concentration* of electricity generation across regions for the respective instrument design. That is, how the generation of electricity to reach the target $\bar{X}$ is divided between regions with a spatially-differentiated or a uniform instrument. If the difference between x_i and x_j is high, the value $x_i x_j$ is lower than if the difference between x_i and x_j is low. In other words, a higher (lower) spatial concentration of electricity generation is reflected by lower (higher) values of the measure $x_i x_j$. The spatial allocation of electricity generation with a uniform instrument, x_i^U, x_j^U, is independent of cumulative environmental effects (11). Only the spatial concentration of electricity generation for a spatially-differentiated instrument, $x_i^* x_j^*$, is affected by cumulative environmental effects (5). Therefore, the presence of cumulative environmental effects alters the welfare differential ΔSC by determining the spatial concentration of electricity generation $x_i^* x_j^*$, such that the term $x_i^U x_j^U - x_i^* x_j^*$ is affected (15). Whenever the difference between $x_i^U x_j^U$ and $x_i^* x_j^*$ is increased (reduced) by the existence of cumulative environmental effects, the welfare differential ΔSC is exacerbated (reduced) as well.

In a next step, we want to know for which levels of cumulative environmental effects the welfare differential is minimal. We set the first derivative of the welfare differential with respect to k equal to zero and solve for k:

$$\frac{\partial \Delta SC}{\partial k} = 0 \qquad \Rightarrow k = \frac{c_i d_j - c_j d_i}{c_i - c_j} = k_A \qquad \text{or} \qquad k = \frac{c_i(c_i+d_i) - c_j(c_j+d_j)}{c_i - c_j} = k_B$$

[1]For a more detailed deduction of $\frac{\partial \Delta SC}{\partial k}$ see Appendix C

The values k_A and k_B represent two extrema of the social cost function[2]. If cumulative environmental effects are equal to either k_A or k_B, the spatial concentration of electricity generation across regions is equal for a spatially-differentiated and a uniform instrument, $x_i^* x_j^* = x_i^U x_j^U$. To characterize the type of extremum represented by k_A and k_B, we insert the two values into the second derivative of the welfare differential with respect to k:

$$\frac{\partial^2 \Delta SC}{\partial k^2} = \frac{(c_i + d_i - c_j - d_j)^2 \bar{X}^2}{(c_i + d_i + c_j + d_j - 2k)^3}$$

$$\frac{\partial^2 \Delta SC}{\partial k^2} \quad 0 \qquad \text{for} \qquad k \lesseqgtr \alpha = \frac{c_i + d_i + c_j + d_j}{2} \tag{16}$$

$$\frac{\partial^2 \Delta SC}{\partial k^2}|_{k=k_A} = \frac{(c_i - c_j)^3 \bar{X}^2}{(c_i + c_j)^3 (c_i + d_i - c_j - d_j)} > 0 \qquad \text{for} \qquad c_i \lesseqgtr c_j \quad \text{and} \quad c_i + d_i \lesseqgtr c_j + d_j \tag{17}$$

$$\frac{\partial^2 \Delta SC}{\partial k^2}|_{k=k_B} = -\frac{(c_i - c_j)^3 \bar{X}^2}{(c_i + c_j)^3 (c_i + d_i - c_j - d_j)} > 0 \qquad \text{for} \qquad c_i \lesseqgtr c_j \quad \text{and} \quad c_i + d_i \quad c_j + d_j \tag{18}$$

Whether k_A and k_B represent the minimum or the maximum of the welfare differential depends on the spatial allocation of generation cost and environmental damage parameters (17, 18).
In the following, we therefore consider two cases to analyse when k_A or k_B minimize the welfare differential ΔSC. The cases are based on different spatial allocations of generation cost and environmental damage parameters.

Case A: More electricity is produced in the same region for a spatially-differentiated and a uniform subsidy

In case A, we assume that electricity generation is cheaper in region i both regarding generation cost parameters $c_i < c_j$ and social cost parameters $c_i + d_i < c_j + d_j$. This applies if generation cost and environmental damage parameters are correlated positively across regions ($c_i < c_j$ and $d_i < d_j$) *or* if the difference in generation cost parameters is higher than in environmental damage parameters ($| c_i - c_j | > | d_i - d_j |$). Thus, in case A more electricity is generated in *the same* region under both regulatory designs:

$$x_i^* > x_j^* \qquad \text{and} \qquad x_i^U > x_j^U$$

$$\frac{\bar{X}(c_j + d_j - k)}{(c_i + d_i + c_j + d_j - 2k)} > \frac{\bar{X}(c_i + d_i - k)}{(c_i + d_i + c_j + d_j - 2k)} \qquad \frac{\bar{X} c_j}{(c_i + c_j)} > \frac{\bar{X} c_i}{(c_i + c_j)}$$

$$c_j + d_j > c_i + d_i \qquad c_j > c_i$$

With (17) we can derive that for this parameter constellation, the minimum of the welfare differential is represented by $k_A = k_A^{min}$. On the contrary, $k_B = k_B^{max}$ represents a local maximum in this case (18).
To understand how cumulative environmental effects alter the welfare differential ΔSC, we compare $k = 0$ to the case $k = 0$. If cumulative environmental effects are not considered, $k = 0$, the

[2] Both values k_A and k_B may be greater, smaller or equal to zero, depending on the specific realization of generation cost and environmental damage parameters.

difference in regional electricity generation for a spatially-differentiated and a uniform instrument depends on the heterogeneity in generation cost parameters and social cost parameters:

$$x_i^* \qquad x_i^U$$

$$\frac{(c_j + d_j - k)\bar{X}}{(c_i + d_i + c_j + d_j - 2k)} \qquad \frac{c_j \bar{X}}{(c_i + c_j)}$$

$$\text{with } k < \alpha \qquad c_i(d_j - k) \quad c_j(d_i - k)$$

$$\text{for } k = 0 \qquad \frac{c_i}{c_j} \quad \frac{d_i}{d_j} \quad \Rightarrow \quad \frac{c_i}{c_j} \quad \frac{c_i + d_i}{c_j + d_j}$$

We first assume that the heterogeneity in generation cost parameters is higher than in social cost parameters. Due to our assumption that $c_i < c_j$ and $c_i + d_i < c_j + d_j$, this is the case if:

$$\frac{c_i}{c_j} < \frac{d_i}{d_j} \quad \Rightarrow \quad \frac{c_i}{c_j} < \frac{c_i + d_i}{c_j + d_j} \quad \Rightarrow \quad x_i^U > x_i^* \quad \Rightarrow \quad x_i^U x_j^U < x_i^* x_j^* \tag{19}$$

$$\frac{\partial \Delta SC}{\partial k} = x_i^U x_j^U - x_i^* x_j^* < 0 \tag{20}$$

Then, more electricity is generated in the region with lower cost parameters with a uniform instrument than with a spatially-differentiated instrument. The spatial concentration of electricity generation is thus higher with a uniform than with a spatially-differentiated instrument (19). When cumulative environmental effects are considered, $k = 0$, their impact on the welfare differential ΔSC depends on their sign and size. If cumulative effects are negative, $k < 0$, they further reduce electricity generation in the region with lower social cost parameters with a spatially-differentiated instrument (5). As a result, electricity generation with a spatially-differentiated instrument is even less concentrated across regions. In other words, the difference between $x_i^* x_j^*$ and $x_i^U x_j^U$ increases. Therefore, the welfare differential increases as well for a marginal decline in $k = 0$ (20). If cumulative environmental effects are positive, however, $k > 0$, electricity generation in the region with lower social cost parameters is enhanced with a spatially-differentiated instrument. Then, the spatial concentration of electricity generation with a spatially-differentiated instrument increases due to the presence of cumulative effects. The difference between $x_i^* x_j^*$ and $x_i^U x_j^U$ is thus reduced, such that the welfare differential is reduced as well for marginal increases in $k = 0$ (20). However, this is only true as long as $x_i^* x_j^* > x_i^U x_j^U$. If k reaches a level such that $x_i^* x_j^* < x_i^U x_j^U$, the welfare differential increases again. For the moment, we focus only on the sign of k. We will analyse the effect of the size of k further below (28).

Next, we assume that the heterogeneity in generation cost parameters is lower than in social cost parameters. That is the case if:

$$\frac{c_i}{c_j} > \frac{d_i}{d_j} \quad \Rightarrow \quad \frac{c_i}{c_j} > \frac{c_i + d_i}{c_j + d_j} \quad \Rightarrow \quad x_i^U < x_i^* \quad \Rightarrow \quad x_i^U x_j^U > x_i^* x_j^* \tag{21}$$

$$\frac{\partial \Delta SC}{\partial k} = x_i^U x_j^U - x_i^* x_j^* > 0 \tag{22}$$

In this case, less electricity is generated in the region with lower cost parameters with a uniform instrument than with a spatially-differentiated instrument. The spatial concentration of electricity generation is then lower with a uniform than with a spatially-differentiated instrument (21).

Again, positive cumulative effects, $k > 0$, enhance electricity generation in the region with lower social cost parameters with a spatially-differentiated instrument (5). The spatial concentration of electricity generation with a spatially-differentiated instrument is increased. However, now this results in an increase in the difference in the spatial concentration of electricity generation with a uniform and a spatially-differentiated instrument. Thus, contrary to the former example, $k > 0$ increases the welfare differential ΔSC (22). When cumulative effects are negative, $k < 0$, they decrease electricity generation in the region with lower social cost parameters with a spatially-differentiated instrument. Then, the spatial concentration of electricity generation with a spatially-differentiated instrument is reduced due to the existence of cumulative effects. As a result, the difference between $x_i^* x_j^*$ and $x_i^U x_j^U$ is reduced and ΔSC is diminished.
When cumulative environmental effects equal k_A^{min}, regional electricity generation is identical for the two regulatory designs, $x_i^U = x_i^*, x_j^U = x_j^*$ (14), such that the welfare differential is equal to zero. The sign of k_A^{min} depends on the heterogeneity in generation cost and social cost parameters as well. If the heterogeneity in generation cost parameters is higher than in social cost parameters, $k_A^{min} > 0$. On the contrary, if the heterogeneity in generation cost parameters is lower than in social cost parameters, $k_A^{min} < 0$.
To sum up, in case A, the impact of cumulative environmental effects on the welfare differential between the two regulatory designs depends both on the heterogeneity in generation cost and social cost parameters and on the sign and size of k. If the heterogeneity in generation cost parameters is higher (lower) than in social cost parameters, negative (positive) cumulative environmental effects always increase the welfare differential. However, positive (negative) cumulative effects may decrease it. Evidently, the sign of k_A^{min} is then also positive (negative). If cumulative effects equal k_A^{min}, the welfare differential is zero.

Case B: More electricity is produced in different regions for a spatially-differentiated and a uniform subsidy
In case B, we change our assumption to $c_i < c_j$ and $c_i + d_i > c_j + d_j$. This is true if generation cost and environmental damage parameters are negatively correlated across regions ($c_i < c_j$ and $d_i > d_j$) *and* if the difference in environmental damage parameters is higher than in generation cost parameters ($| c_i - c_j | < | d_i - d_j |$). Thus, in case B more electricity is generated in *different* regions for a spatially-differentiated and a uniform instrument:

$$\begin{array}{ccc} x_i^* < x_j^* & \text{and} & x_i^U > x_j^U \\ c_j + d_j < c_i + d_i & & c_j > c_i \end{array}$$

From (18) we know that now the welfare differential ΔSC is minimal if cumulative environmental effects are equal to $k_B = k_B^{min}$. The value $k_A = k_A^{max}$ represents a local maximum (17).
Again, if cumulative environmental effects are neglected, $k = 0$, the difference in regional electricity generation for the two regulatory designs depends on the spatial heterogeneity in generation cost parameters and social cost parameters. However, because in case B more electricity is generated in different regions with a spatially-differentiated and a uniform instrument, electricity

generations for opposite regions are compared:

	x_j^*	x_i^U
	$\frac{(c_i + d_i - k)\bar{X}}{(c_i + d_i + c_j + d_j - 2k)}$	$\frac{c_j \bar{X}}{(c_i + c_j)}$
with $k < \alpha$	$c_i(c_i + d_i - k)$	$c_j(c_j + d_j - k)$
for $k = 0$	$\frac{c_i}{c_j}$	$\frac{(c_j + d_j)}{(c_i + d_i)}$

Like in case A, we first assume that the heterogeneity in generation cost parameters is higher than in social cost parameters. Because of the assumption that $c_i < c_j$ and $c_i + d_i > c_j + d_j$, this is the case if:

$$\frac{c_i}{c_j} < \frac{(c_j + d_j)}{(c_i + d_i)} \qquad \Rightarrow \qquad x_i^U > x_j^* \qquad \Rightarrow \qquad x_i^U x_j^U < x_i^* x_j^* \tag{23}$$

$$\frac{\partial \Delta SC}{\partial k} = x_i^U x_j^U - x_i^* x_j^* < 0 \tag{24}$$

Then, more electricity is generated in the region with lower generation cost parameters under a uniform instrument than in the region with lower social cost parameters under a spatially-differentiated instrument. The spatial concentration of electricity generation is thus higher with a uniform than with a spatially-differentiated regulation (23).

Again, we are interested in how cumulative environmental effects alter the welfare differential. If cumulative effects are negative, $k < 0$, electricity generation in the region with lower social cost parameters decreases under a spatially-differentiated instrument (5). Thus, the spatial concentration of electricity generation with a spatially-differentiated instrument is reduced. The difference between $x_i^* x_j^*$ and $x_i^U x_j^U$ amplifies and the welfare differential increases (24). If cumulative environmental effects are positive, $k > 0$, electricity generation in the region with lower social cost parameters rises. Then, the spatial concentration of electricity generation with a spatially-differentiated instrument increases and the difference between $x_i^* x_j^*$ and $x_i^U x_j^U$ is reduced. The welfare differential decreases as well (24).

We now presume that the heterogeneity in generation cost parameters is lower than in social cost parameters:

$$\frac{c_i}{c_j} > \frac{(c_j + d_j)}{(c_i + d_i)} \qquad \Rightarrow \qquad x_i^U < x_j^* \qquad \Rightarrow \qquad x_i^U x_j^U > x_i^* x_j^* \tag{25}$$

$$\frac{\partial \Delta SC}{\partial k} = x_i^U x_j^U - x_i^* x_j^* > 0 \tag{26}$$

The spatial concentration of electricity generation is thus lower with a uniform than with a spatially-differentiated instrument (25). Positive cumulative environmental effects, $k > 0$, further enhance electricity generation in the region with lower social cost parameters with a spatially-differentiated regulation. The spatial concentration of electricity generation for this instrument design is then increased. The difference between $x_i^U x_j^U$ and $x_i^* x_j^*$ thus rises and the welfare differential increases as well for $k > 0$ (26). Thus, as in case A, the impact of cumulative effects on the welfare differential is now reversed. If cumulative environmental effects are negative, $k < 0$, they result in a decrease of the spatial concentration of electricity generation with a spatially-differentiated instrument. The spatial concentration of electricity generation under the two regulatory designs then becomes more similar, i.e. the difference between $x_i^U x_j^U$ and $x_i^* x_j^*$ is reduced. As a result, the welfare differential decreases (26).

In case B, the welfare differential is minimized if $k = k_B$. Then, regional electricity generation is perfectly opposed for a spatially-differentiated and a uniform instrument, i.e. $x_i^U = x_j^*$ and $x_j^U = x_i^*$. The spatial concentration of electricity generation is hence equal for the two regulatory designs $x_i^U x_j^U = x_i^* x_j^*$. However, the welfare differential is still greater than zero, because regional electricity generation diverges for the two instrument designs:

$$\Delta SC|_{k=k_B^{min}} = \frac{-(c_i - c_j)(c_i + d_i - c_j - d_j)\bar{X}^2}{2(c_i + c_j)} \tag{27}$$

$$\Delta SC|_{k=k_B^{min}} > 0 \qquad \text{for} \qquad c_i \quad c_j \qquad \text{and} \qquad c_i + d_i \quad c_j + d_j$$

As in case A, the sign of k_B^{min} relies on the spatial heterogeneity of generation cost and social cost parameters. If generation cost parameters vary more than social cost parameters at a spatial scale, $k_B^{min} > 0$. Otherwise, $k_B^{min} < 0$.

Overall, in case B, we can identify the same rule for the impact of cumulative environmental effects on the welfare differential between a spatially-differentiated and a spatially-uniform instrument. If the heterogeneity in generation cost parameters is higher (lower) than in social cost parameters, negative (positive) cumulative effects always increase the welfare differential. Yet, positive (negative) cumulative effects may decrease or even minimize the welfare differential. Accordingly, k_B^{min} is positive (negative).

The marginal impact of the cumulative effect k on ΔSC in cases A and B is summarized in detail in table 1 below.

Assumption: Based on different spatial distributions of generation cost parameters and social cost parameters, more electricity is generated in the *same* or in *different* regions for s_i^*, s_j^* and s^U.	*Assumption:* Heterogeneity in generation cost parameters and social cost parameters	*Assumption:* Level of cumulative environmental effects compared to k^{min}.	*Implication:* Concentration of electricity generation across regions for s^U and s_i^*, s_j^*	*Implication:* Marginal impact of cumulative environmental effects on the welfare differential $\Delta SC = SC^U - SC^*$
	$\frac{c_i}{c_j} \lessgtr \frac{c_i+d_i}{c_j+d_j}$, $\frac{c_i}{c_j} \lessgtr \frac{c_j+d_j}{c_i+d_i}$	$\|k\| \quad \|k^{min}\|$	$x_i^U x_j^U \quad x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} = x_i^U x_j^U - x_i^* x_j^*$
Case A: Same region $k_A^{min} = \frac{c_i d_j - c_j d_i}{c_i - c_j}$		$k = k_A^{min}$	$x_i^U x_j^U = x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} = 0, \Delta SC = 0$
$c_i < c_j$	$\frac{c_i}{c_j} < \frac{c_i+d_i}{c_j+d_j}$	$\|k\| < \|k_A^{min}\|$	$x_i^U x_j^U < x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} < 0$
$c_i + d_i < c_j + d_j$		$\|k\| > \|k_A^{min}\|$	$x_i^U x_j^U > x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} > 0$
	$\frac{c_i}{c_j} > \frac{c_i+d_i}{c_j+d_j}$	$\|k\| < \|k_A^{min}\|$	$x_i^U x_j^U > x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} > 0$
		$\|k\| > \|k_A^{min}\|$	$x_i^U x_j^U < x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} < 0$
$c_i > c_j$	$\frac{c_i}{c_j} < \frac{c_i+d_i}{c_j+d_j}$	$\|k\| < \|k_A^{min}\|$	$x_i^U x_j^U > x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} > 0$
$c_i + d_i > c_j + d_j$		$\|k\| > \|k_A^{min}\|$	$x_i^U x_j^U < x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} < 0$
	$\frac{c_i}{c_j} > \frac{c_i+d_i}{c_j+d_j}$	$\|k\| < \|k_A^{min}\|$	$x_i^U x_j^U < x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} < 0$
		$\|k\| > \|k_A^{min}\|$	$x_i^U x_j^U > x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} > 0$
Case B: Different regions $k_B^{min} = \frac{c_i(c_i+d_i) - c_j(c_j+d_j)}{c_i - c_j}$		$k = k_B^{min}$	$x_i^U x_j^U = x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} = 0,\ \Delta SC > 0$
$c_i < c_j$	$\frac{c_i}{c_j} < \frac{c_j+d_j}{c_i+d_i}$	$\|k\| < \|k_B^{min}\|$	$x_i^U x_j^U < x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} < 0$
$c_i + d_i > c_j + d_j$		$\|k\| > \|k_B^{min}\|$	$x_i^U x_j^U > x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} > 0$
	$\frac{c_i}{c_j} > \frac{c_j+d_j}{c_i+d_i}$	$\|k\| < \|k_B^{min}\|$	$x_i^U x_j^U > x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} > 0$
		$\|k\| > \|k_B^{min}\|$	$x_i^U x_j^U < x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} < 0$
$c_i > c_j$	$\frac{c_i}{c_j} < \frac{c_j+d_j}{c_i+d_i}$	$\|k\| < \|k_B^{min}\|$	$x_i^U x_j^U > x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} > 0$
$c_i + d_i < c_j + d_j$		$\|k\| > \|k_B^{min}\|$	$x_i^U x_j^U < x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} < 0$
	$\frac{c_i}{c_j} > \frac{c_j+d_j}{c_i+d_i}$	$\|k\| < \|k_B^{min}\|$	$x_i^U x_j^U < x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} < 0$
		$\|k\| > \|k_B^{min}\|$	$x_i^U x_j^U > x_i^* x_j^*$	$\frac{\partial \Delta SC}{\partial k} > 0$

Table 1: Impact of an increase in cumulative environmental effects k on the welfare differential between a spatially-differentiated and a uniform regulation ΔSC for different spatial correlations and levels of spatial heterogeneity in generation cost parameters c_i, c_j and social cost parameters $c_i + d_i, c_j + d_j$.

In both cases A and B, the impact of cumulative environmental effects on the welfare differential between a spatially-differentiated and a uniform instrument depends on the sign of the cumulative effect k. If k and k^{min} display different signs, the existence of cumulative effects increases the welfare differential as compared to the case $k = 0$. However, if k and k^{min} display the same sign, cumulative effects may decrease the welfare differential ΔSC as compared to the case $k = 0$. Whether this is the case additionally depends on the *size* of cumulative environmental effects. Therefore, we calculate the welfare differential for $k = 0$ and derive the size of the cumulative environmental effect k^0 for which the welfare differential is identical:

$$\Delta SC|_{k=0} = \frac{(c_i d_j - c_j d_i)^2 \bar{X}^2}{2(c_i + c_j)^2 (c_i + d_i + c_j + d_j)}$$

$$\Delta SC = \Delta SC|_{k=0} \qquad \Rightarrow \qquad k = \frac{2(c_j d_i - c_i d_j)(c_j(c_j + d_j) - c_i(c_i + d_i))}{(c_i - c_j)^2 (c_i + d_i + c_j + d_j)} = k^0 \tag{28}$$

The welfare differential is equal for the two values $k = 0$ and $k = k^0$. Thus, the welfare differential between a spatially-differentiated and a uniform instrument is decreased by the

existence of cumulative environmental effects if $0 < k < k^0$ or $k^0 < k < 0$. If $|k| > |k^0|$, the welfare differential is increased instead.
Our results show that the existence of cumulative environmental effects may either enhance or reduce the welfare differential between a spatially-differentiated and a uniform instrument. Which of the options applies depends on the sign and size of cumulative environmental effects as well as on the spatial heterogeneity of generation cost and social cost parameters. If the heterogeneity in generation cost parameters is higher (lower) than in social cost parameters and cumulative environmental effects are negative (positive), cumulative environmental effects always increase the welfare differential. However, if the heterogeneity in generation cost parameters is higher (lower) than in social cost parameters, positive (negative) cumulative environmental effects may decrease the welfare differential as opposed to the case $k = 0$. This is true as long as the absolute value of cumulative effects does not exceed the absolute value of k^0. Whenever cumulative effects are equal to the value k^{min}, the welfare differential is minimal.

5 Numerical Calibration

In the theoretical model, we demonstrate that cumulative environmental effects, in addition to spatially-varying environmental damages, matter for the efficient regulation of RES deployment. Next, we want to generate insights on the empirical relevance of cumulative environmental effects and spatially heterogeneous environmental damages for optimal RES deployment. We therefore calibrate our model for the example of electricity generation from onshore wind power in Germany.

5.1 Set up

For the calibration, the regions from the theoretical model are represented by the German federal states. We focus on neighbouring federal states because, with the present knowledge on cumulative environmental effects, we assume it most realistic that these effects occur between spatially connected regions. Furthermore, we exclude the German city states as well as the state Saarland from our calibration. Thus, we only consider the territorial federal states. The reason for this is that onshore wind power plants can only be deployed at a significant level in federal states that command a sufficient amount of space for the deployment[3]. Consequently, we calibrate our model for the twelve remaining territorial federal states[4], which results in the analysis of 24 pairs of neighbouring states.
For each state, we use the quadratic generation cost function:

$$C_i(x_i) = c_{1i}x_i + \frac{c_{2i}}{2}x_i^2 \qquad i = 1, ..., 12 \tag{29}$$

[3]This is also reflected by the current deployment status of onshore wind power in the German federal states. The city states Berlin, Hamburg and Bremen as well as the state Saarland display the lowest numbers in both wind turbines installend and installed capacities, as compared to the remaining federal states (Deutsche WindGuard GmbH, 2020).

[4]We consider the twelve territorial German federal states Baden-Wuerttemberg (BW), Bavaria (BY), Brandenburg (BB), Hessia (HE), Mecklenburg-Western Pomerania (MV), Lower Saxony (NI), North Rhine-Westphalia (NW), Rhineland-Palatinate (RP), Saxony (SN), Saxony-Anhalt (ST), Schleswig-Holstein (SH), Thuringia (TH)

The two coefficients c_{1i} and $\frac{c_{2i}}{2}$ are estimated for each state in a linear regression model by Meier and Lehmann (2020) based on site-specific levelized cost of electricity (LCOE) from Tafarte and Lehmann (2019). For each federal state, aggregate wind power generation costs are thus approximated by the quadratic function (29). Respective state-specific coefficients are specified in Appendix D.

Equivalently, environmental damage coefficients for each state are estimated with a regression model by Meier and Lehmann (2020) based on site-specific data for environmental damages from Tafarte and Lehmann (2019). Based on the regression results, state-specific environmental damages can be approximated by a quadratic function:

$$D_i(x_i) = \frac{d_i}{2}x_i^2 \qquad i = 1, ..., 12 \tag{30}$$

The state-specific coefficients d_i for region-specific environmental damages may also be found in Appendix D. In our calibration example, we focus on damages caused by onshore wind power turbines for residents. Tafarte and Lehmann (2019) compute site-specific environmental damages as a function of the distance of a household to the wind turbine and aggregate over all households living in a 4km radius of a site. Environmental damage levels for different turbine-settlement distances are based on people's willingness to pay (WTP) for different buffer zones between turbines and their residence. Environmental damages rise as the distance of turbine-sites to settlements decreases. In this setup, heterogeneity of environmental damages at the federal state level stems from different levels of proximity between turbine sites and households and different population sizes in each state.

As in the theoretical model, aggregate environmental damages amount to:

$$D(x_i, x_j) = \frac{d_i}{2}x_i^2 + \frac{d_j}{2}x_j^2 + kx_ix_j \quad i = j \tag{31}$$

In our calibration example, cumulative environmental effects can arise due to distributive justice preferences at a spatial scale. If these preferences call for a spatially more even allocation of wind turbines across regions, this implies that residents perceive wind turbines as less disturbing if they are sited in both regions. The corresponding cumulative impact parameter is then negative, $k < 0$. However, we refrain from assumptions regarding the sign and size of the cumulative environmental effect parameter k. The main reason for this is that the model calibration aims at understanding the sensitivity of the welfare differential between a spatially-uniform and a spatially-differentiated regulation regarding cumulative environmental effects. In addition, to our knowledge no valid empirical estimations for k exist to date.

Due to the assumption of quadratic generation costs (1) and quadratic environmental damages (2) in the theoretical model, the generation target $\bar{X}$ disproportionately increases the welfare differential between a spatially-differentiated and a uniform regulation (13). Therefore, to support the comparability of the calibrated results across the 24 pairs of neighbouring federal states, we use the same aggregate electricity production target for onshore wind power for each state pair. The target is derived by first setting the national electricity generation objective for onshore wind power at 250 TWh. This level corresponds to the amount of onshore wind power that is approximately needed to fulfil the German renewable energy generation targets for 2033 (Agora

Energiewende, 2013). Second, we simplify by assuming that each federal state can theoretically contribute the same amount of electricity generation from onshore wind power to achieve the national target[5]. Therefore, the generation target at the federal state level is set to $\frac{250TWh}{12} = 20.83$ TWh. Finally, to achieve the electricity generation target for two states, $\bar{X}$, the federal target is doubled. Thus, we assume $\bar{X} = \frac{250}{6} = 41.67$ TWh.

5.2 Results

The calibration results for the 24 pairs of neighbouring federal states are displayed in table 2. The first column of table 2 shows the pairs of neighbouring federal states, while the second column characterizes whether the state pair represents case A or case B from the theoretical model. In 20 pairs of neighbouring states, the majority of electricity from onshore wind power to reach the target $\bar{X}$ is generated in the same state under both a spatially-differentiated and a spatially-uniform regulation (case A). This can be derived from the third and fourth column of table 2, which display the ratio of regional electricity generation levels for the two regulatory designs. In the remaining four state pairs, the majority of $\bar{X}$ is generated in different states for a spatially-differentiated and a spatially-uniform instrument (case B).
The calibration results confirm that both heterogeneity in generation costs and region-specific environmental damage parameters as well as cumulative environmental effects impact the welfare differential between a spatially-differentiated and uniform instrument design.

5.2.1 Heterogeneity in generation cost and environmental damage parameters

First, the effect of spatial heterogeneity in generation cost parameters and environmental damage parameters on the welfare differential between the two regulatory designs is assessed if cumulative environmental effects are neglected, i.e. assuming $k = 0$. The coefficients c_{1i}, c_{2i} and d_i, d_j suggest that both generation cost and environmental damage parameters vary considerably across the German federal states (see Appendix D). While linear coefficients c_{1i} of generation costs range from 0.040 in Lower Saxony to 0.062 in Baden-Wuerttemberg, quadratic coefficients c_{2i} display higher levels of variation, ranging from $1.42 \cdot 10^{-13}$ in Mecklenburg-Western Pomerania to $2.52 \cdot 10^{-12}$ in Rhineland-Palatinate. Environmental damage coefficients d_i vary even more, ranging from $4.29 \cdot 10^{-13}$ in Mecklenburg-Western Pomerania to $2.11 \cdot 10^{-11}$ in Rhineland-Palatinate. In the absence of cumulative environmental effects, this heterogeneity translates into considerable welfare losses associated with a spatially-uniform as opposed to a spatially-differentiated regulation of electricity generation. As demonstrated in column eight of table 2, the respective welfare differential $\Delta SC|_{k=0}$ may become as high as $2.22 \cdot 10^9$€ for the state pair North Rhine-Westphalia (NW) and Rhineland-Palatinate (RP).
Furthermore, the calibration indicates that similar regional allocations of electricity generation, x_i, x_j, for the two regulatory designs need not coincide with lower levels of the corresponding welfare differential. This insight is visualised in figure 1 below. Neighbouring states with smaller

[5]Of course, in reality, the number of potential sites for onshore wind turbines and therefore the possible contribution to a national electricity generation target differs across the German federal states (Masurowski et al., 2016).

differences between state-specific electricity generation, i.e. with lower differences $\frac{x_i^*}{x_j^*} - \frac{x_i^U}{x_j^U}$, can display both lower and higher levels of the respective welfare differential (dots close to the y-axis). The same is true for state pairs with higher differences between state-specific electricity generation ratios (dots further away from the y-axis). This result is based on the heterogeneity of generation cost and environmental damage parameters. Even small deviations from the socially optimal spatial allocation of electricity generation across regions may eventuate in high welfare losses if the disparity of generation cost and environmental damage parameters across regions is pronounced.

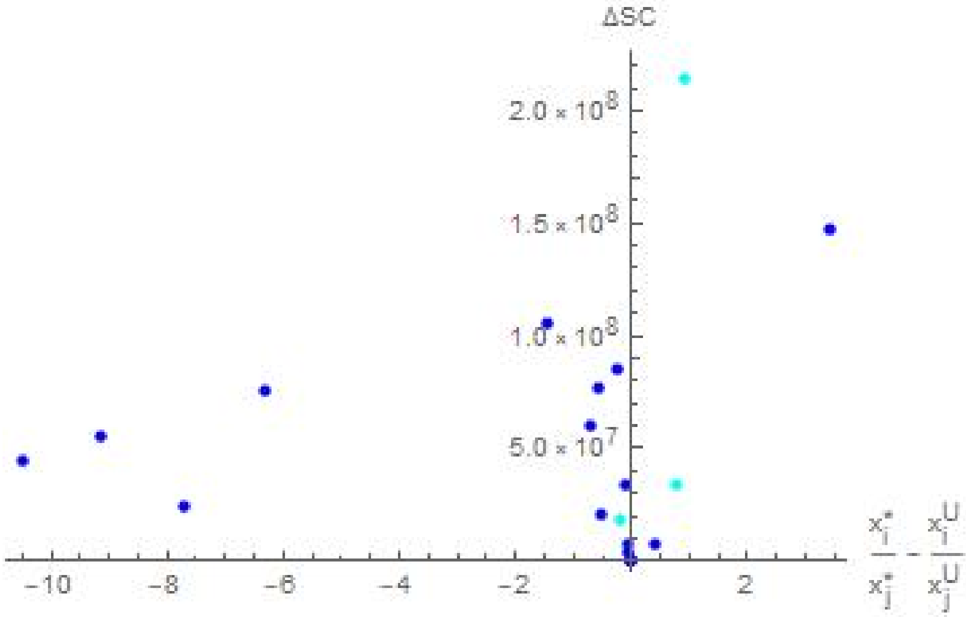

Figure 1: Correlation between the difference in state electricity generation ratios for a spatially-differentiated and a uniform instrument ($\frac{x_i^*}{x_j^*} - \frac{x_i^U}{x_j^U}$) and the corresponding welfare differential (ΔSC). Case A state pairs are represented by dark blue dots, case B state pairs are represented by light blue dots. Results for neighbouring states NW and HE, NW and RP as well as NI and NW are not depicted in the figure. Because these cases display relatively high levels for ΔSC (NWHE, NWRP) or because the difference $\frac{x_i^*}{x_j^*} - \frac{x_i^U}{x_j^U}$ is relatively high (NINW), they have been excluded for the sake of illustration.

States	Case	Ratio of optimal quantities	Ratio of uniform quantities	k^{min}, in case A: k_A^{min}, in case B: k_B^{min}	Ratio k^{min} to state-specific damages d_i, d_j	Ratio k^0 to state-specific damages d_i, d_j	Welfare differential for $k=0$	Wel-fare ranking $k=0$	Welfare differential for $k=k^{min}$
i, j	A,B	$\frac{x_i^*}{x_j^*}\|_{k=0}$	$\frac{x_i^U}{x_j^U}$	k_A^{min}, k_B^{min}	$\frac{k^{min}}{d_i}$, $\frac{k^{min}}{d_j}$	$\frac{k^0}{d_i}$, $\frac{k^0}{d_j}$	$\Delta SC\|_{k=0}$	#	$\Delta SC\|_{k=k^{min}}$
$i=$ SH, $j=$ MV	A	0.13	0.25	$k_A^{min} = -7.61 \cdot 10^{-14}$	$\frac{k_A^{min}}{d_{SH}} = -0.19$ $\frac{k_A^{min}}{d_{MV}} = -1.77$	$\frac{k^0}{d_{SH}} = -0.45$ $\frac{k^0}{d_{MV}} = -4.07$	$3.44 \cdot 10^7$	13	~ 0
$i=$ SH, $j=$ NI	A	0.22	0.27	$k_A^{min} = -2.92 \cdot 10^{-13}$	$\frac{k_A^{min}}{d_{SH}} = -0.07$ $\frac{k_A^{min}}{d_{NI}} = -0.35$	$\frac{k^0}{d_{SH}} = -0.16$ $\frac{k^0}{d_{NI}} = -0.73$	$4.34 \cdot 10^6$	5	0
$i=$ MV, $j=$ BB	A	1.69	7.99	$k_A^{min} = 4.28 \cdot 10^{-13}$	$\frac{k_A^{min}}{d_{MV}} = 1.00$ $\frac{k_A^{min}}{d_{BB}} = 0.98$	$\frac{k^0}{d_{MV}} = 1.33$ $\frac{k^0}{d_{BB}} = 1.30$	$7.53 \cdot 10^7$	17	~ 0
$i=$ MV, $j=$ NI	B	1.62	0.86	$k_B^{min} = -1.85 \cdot 10^{-12}$	$\frac{k_B^{min}}{d_{MV}} = -4.30$ $\frac{k_B^{min}}{d_{NI}} = -2.20$	$\frac{k^0}{d_{MV}} = -18.40$ $\frac{k^0}{d_{NI}} = -9.40$	$3.38 \cdot 10^7$	12	$2.42 \cdot 10^7$
$i=$ BB, $j=$ ST	A	5.48	2.08	$k_A^{min} = -2.85 \cdot 10^{-12}$	$\frac{k_A^{min}}{d_{BB}} = -6.51$ $\frac{k_A^{min}}{d_{ST}} = -0.72$	$\frac{k^0}{d_{BB}} = -19.38$ $\frac{k^0}{d_{ST}} = -2.13$	$1.48 \cdot 10^8$	21	~ 0
$i=$ BB, $j=$ SN	A	1.62	1.22	$k_A^{min} = -1.18 \cdot 10^{-12}$	$\frac{k_A^{min}}{d_{BB}} = -2.71$, $\frac{k_A^{min}}{d_{SN}} = -1.50$	$\frac{k^0}{d_{BB}} = -9.27$ $\frac{k^0}{d_{SN}} = -5.15$	$6.95 \cdot 10^6$	6	0
$i=$ BB, $j=$ NI	B	1.07	0.16	$k_B^{min} = 8.40 \cdot 10^{-13}$	$\frac{k_B^{min}}{d_{BB}} = 1.92$ $\frac{k_B^{min}}{d_{NI}} = 1.00$	$\frac{k^0}{d_{BB}} = 2.01$ $\frac{k^0}{d_{NI}} = 1.05$	$2.15 \cdot 10^8$	22	$3.54 \cdot 10^7$
$i=$ ST, $j=$ NI	A	0.22	0.24	$k_A^{min} = -1.25 \cdot 10^{-13}$	$\frac{k_A^{min}}{d_{ST}} = -0.03$ $\frac{k_A^{min}}{d_{NI}} = -0.15$	$\frac{k^0}{d_{ST}} = -0.06$ $\frac{k^0}{d_{NI}} = -0.30$	845066	4	0
$i=$ ST, $j=$ TH	B	0.84	1.02	$k_B^{min} = -3.36 \cdot 10^{-11}$	$\frac{k_B^{min}}{d_{ST}} = -8.45$ $\frac{k_B^{min}}{d_{TH}} = -10.58$	$\frac{k^0}{d_{ST}} = -79.36$ $\frac{k^0}{d_{TH}} = -99.34$	$1.81 \cdot 10^7$	8	*

States	Case	Ratio of optimal quantities	Ratio of uniform quantities	k^{min}, in case A: k_A^{min}, in case B: k_B^{min}	Ratio k^{min} to state-specific damages d_i, d_j	Ratio k^0 to state-specific damages d_i, d_j	Welfare differential for $k=0$	Wel-fare ranking $k=0$	Welfare differential for $k=k^{min}$
i, j	A,B	$\frac{x_i^*}{x_j^*}\|_{k=0}$	$\frac{x_i^U}{x_j^U}$	k_A^{min}, k_B^{min}	$\frac{k^{min}}{d_i}$, $\frac{k^{min}}{d_j}$	$\frac{k^0}{d_i}$, $\frac{k^0}{d_j}$	$\Delta SC\|_{k=0}$	#	$\Delta SC\|_{k=k^{min}}$
$i=$ ST, $j=$ SN	A	0.25	0.49	$k_A^{min} = -2.25 \cdot 10^{-12}$	$\frac{k_A^{min}}{d_{ST}} = -0.57$ $\frac{k_A^{min}}{d_{SN}} = -2.85$	$\frac{k^0}{d_{ST}} = -1.55$ $\frac{k^0}{d_{SN}} = -7.81$	$8.53 \cdot 10^7$	19	~ 0
$i=$ NI, $j=$ TH	A	4.52	13.66	$k_A^{min} = 6.56 \cdot 10^{-13}$	$\frac{k_A^{min}}{d_{NI}} = 0.78$ $\frac{k_A^{min}}{d_{TH}} = 0.21$	$\frac{k^0}{d_{NI}} = 1.36$ $\frac{k^0}{d_{TH}} = 0.36$	$5.56 \cdot 10^7$	15	~ 0
$i=$ NI, $j=$ HE	A	5.66	16.16	$k_A^{min} = 6.29 \cdot 10^{-13}$	$\frac{k_A^{min}}{d_{NI}} = 0.75$ $\frac{k_A^{min}}{d_{HE}} = 0.16$	$\frac{k^0}{d_{NI}} = 1.34$ $\frac{k^0}{d_{HE}} = 0.28$	$4.43 \cdot 10^7$	14	~ 0
$i=$ NI, $j=$ NW	A	28.13	**	$k_A^{min} = 1.15 \cdot 10^{-12}$	$\frac{k_A^{min}}{d_{NI}} = 1.37$ $\frac{k_A^{min}}{d_{NW}} = 0.05$	$\frac{k^0}{d_{NI}} = 1.87$ $\frac{k^0}{d_{NW}} = 0.07$	$2.42 \cdot 10^7$	10	0
$i=$ NW, $j=$ HE	A	0.22	0.53	$k_A^{min} = -1.51 \cdot 10^{-11}$	$\frac{k_A^{min}}{d_{NW}} = -0.72$ $\frac{k_A^{min}}{d_{HE}} = -3.75$	$\frac{k^0}{d_{NW}} = -2.23$ $\frac{k^0}{d_{HE}} = -11.61$	$6.82 \cdot 10^8$	23	0
$i=$ NW, $j=$ RP	B	0.52	1.61	$k_B^{min} = -5.95 \cdot 10^{-12}$	$\frac{k_B^{min}}{d_{NW}} = -0.28$ $\frac{k_B^{min}}{d_{RP}} = -0.64$	$\frac{k^0}{d_{NW}} = -0.66$ $\frac{k^0}{d_{RP}} = -1.49$	$2.22 \cdot 10^9$	24	$2.18 \cdot 10^9$
$i=$ HE, $j=$ RP	A	2.43	2.93	$k_A^{min} = 1.28 \cdot 10^{-12}$	$\frac{k_A^{min}}{d_{HE}} = 0.32$ $\frac{k_A^{min}}{d_{RP}} = 0.14$	$\frac{k^0}{d_{HE}} = 0.59$ $\frac{k^0}{d_{RP}} = 0.25$	$2.04 \cdot 10^7$	9	~ 0
$i=$ HE, $j=$ BW	A	2.42	3.89	$k_A^{min} = 2.35 \cdot 10^{-12}$	$\frac{k_A^{min}}{d_{HE}} = 0.58$ $\frac{k_A^{min}}{d_{BW}} = 0.26$	$\frac{k^0}{d_{HE}} = 0.99$ $\frac{k^0}{d_{BW}} = 0.45$	$1.06 \cdot 10^8$	20	~ 0
$i=$ HE, $j=$ BY	A	1.25	1.82	$k_A^{min} = 3.38 \cdot 10^{-12}$	$\frac{k_A^{min}}{d_{HE}} = 0.84$ $\frac{k_A^{min}}{d_{BY}} = 0.74$	$\frac{k^0}{d_{HE}} = 1.16$ $\frac{k^0}{d_{BY}} = 1.02$	$7.64 \cdot 10^7$	18	0
$i=$ HE, $j=$ TH	A	0.79	0.82	$k_A^{min} = -8.30 \cdot 10^{-13}$	$\frac{k_A^{min}}{d_{HE}} = -0.21$ $\frac{k_A^{min}}{d_{TH}} = -0.26$	$\frac{k^0}{d_{HE}} = -0.45$ $\frac{k^0}{d_{TH}} = -0.57$	639342	3	~ 0

States i, j	Case A,B	Ratio of optimal quantities $\frac{x_i^*}{x_j^*}\|_{k=0}$	Ratio of uniform quantities $\frac{x_i^U}{x_j^U}$	k^{min}, in case A: k_A^{min}, in case B: k_B^{min} — k_A^{min}, k_B^{min}	Ratio k^{min} to state-specific damages d_i, d_j — $\frac{k^{min}}{d_i}$, $\frac{k^{min}}{d_j}$	Ratio k^0 to state-specific damages d_i, d_j — $\frac{k^0}{d_i}$, $\frac{k^0}{d_j}$	Welfare differential for $k=0$ $\Delta SC\|_{k=0}$	Wel-fare ranking $k=0$ #	Welfare differential for $k=k^{min}$ $\Delta SC\|_{k=k^{min}}$
$i=$ TH, $j=$ SN	A	0.26	0.34	$k_A^{min} = -4.24 \cdot 10^{-13}$	$\frac{k_A^{min}}{d_{TH}} = -0.13$ $\frac{k_A^{min}}{d_{SN}} = -0.54$	$\frac{k^0}{d_{TH}} = -0.29$ $\frac{k^0}{d_{SN}} = -1.17$	$7.82 \cdot 10^6$	7	0
$i=$ TH, $j=$ BY	A	1.59	2.30	$k_A^{min} = 2.09 \cdot 10^{-12}$	$\frac{k_A^{min}}{d_{TH}} = 0.66$ $\frac{k_A^{min}}{d_{BY}} = 0.46$	$\frac{k^0}{d_{TH}} = 1.04$ $\frac{k^0}{d_{BY}} = 0.72$	$5.95 \cdot 10^7$	16	~ 0
$i=$ SN, $j=$ BY	A	6.77	14.49	$k_A^{min} = 5.07 \cdot 10^{-13}$	$\frac{k_A^{min}}{d_{SN}} = 0.64$ $\frac{k_A^{min}}{d_{BY}} = 0.11$	$\frac{k^0}{d_{SN}} = 1.19$ $\frac{k^0}{d_{BY}} = 0.20$	$2.46 \cdot 10^7$	11	~ 0
$i=$ RP, $j=$ BW	A	0.96	0.68	$k_A^{min} = -8.79 \cdot 10^{-12}$	$\frac{k_A^{min}}{d_{RP}} = -0.94$ $\frac{k_A^{min}}{d_{BW}} = -0.98$	$\frac{k^0}{d_{RP}} = -2.61$ $\frac{k^0}{d_{BW}} = -2.73$	410205	2	~ 0
$i=$ BW, $j=$ BY	A	0.51	0.52	$k_A^{min} = -2.26 \cdot 10^{-13}$	$\frac{k_A^{min}}{d_{BW}} = -0.03$ $\frac{k_A^{min}}{d_{BY}} = -0.05$	$\frac{k^0}{d_{BW}} = -0.05$ $\frac{k^0}{d_{BY}} = -0.10$	257361	1	~ 0

Table 2: Influence of the level of cumulative environmental effects k on the welfare differential between a spatially-uniform and a spatially-differentiated regulation.
* For the state pair ST and TH, $SC^*|_{k=k_B^{min}} < 0$ because the value $k_B^{min} < 0$ is too low. Therefore, the calculation for $\Delta SC|_{k=k_B^{min}}$ is misleading and omitted in this tabular. ** For the state pair NW and NI, a uniform regulation results in the corner solution $x_{NI}^U = \bar{X}, x_{NW}^U = 0$.

5.2.2 Cumulative environmental effects

In addition to the heterogeneity of generation cost parameters and environmental damage parameters, the presence of cumulative environmental effects, $k = 0$, considerably influences the welfare gains of a spatially-differentiated instrument design. For neighbouring states representing both case A or B, these gains may be reduced or increased by cumulative environmental effects. The possible decrease of the welfare differential between a spatially-differentiated and uniform instrument due to the existence of cumulative effects is maximal if $k = k^{min}$ (column five in table 2). The level of this reduction, captured in the last column of table 2, is mostly higher in cases A than in cases B, because in cases A, cumulative effects might result in identical state-specific electricity generation for the two instrument designs. For example, consider the case B neighbouring states Mecklenburg-Western Pomerania (MV) and Lower Saxony (NI). The existence of cumulative environmental effects may reduce the welfare differential between a spatially-differentiated and a spatially-uniform regulation of wind power development in these states by up to 28% or 9.57 million Euro. In North Rhine-Westphalia (NW) and Rhineland-Palatinate (RP), similarly case B, the welfare differential may be reduced by up to 2% or 48.1 million Euro. In neighbouring states representing case A, cumulative effects could potentially reduce the welfare differential to zero, resulting in a maximal relative reduction of 100%. Also in absolute terms, possible changes in the welfare differential in case A mostly exceed the changes in case B. For example, the welfare differential in North Rhine-Westphalia (NW) and Hessia (HE), case A, may be diminished by 682 million Euro due to cumulative environmental effects, which is the highest possible absolute amount for all state combinations.

Recall from the theoretical model that whether cumulative environmental effects actually reduce the welfare differential between a spatially-differentiated and uniform instrument design is contingent on two factors: the sign and the size of k. First, cumulative environmental effects only reduce the welfare differential if they display the same sign as the value k^{min}. Otherwise, the welfare differential is accentuated rather than diminished by the existence of cumulative environmental effects. Second, if k^{min} and k display the same sign, only cumulative environmental effects $|k| < |k^0|$ reduce the welfare differential between a spatially-differentiated and uniform regulation. If cumulative environmental effects exceed this level, the welfare differential is enhanced as compared to $k = 0$. These findings are illustrated by two case A examples.

For the state pair North Rhine-Westphalia (NW) and Hessia (HE), the ratios of regional electricity generation show that more electricity is produced in Hessia for both instrument designs, $\frac{x^*_{NW}}{x^*_{HE}}, \frac{x^U_{NW}}{x^U_{HE}} < 1$ (case A). However, the concentration of electricity generation in Hessia is higher for the spatially-differentiated than for the uniform regulation, $\frac{x^*_{NW}}{x^*_{HE}} < \frac{x^U_{NW}}{x^U_{HE}}$. Negative cumulative environmental effects favour a lower concentration of electricity generation in Hessia with a spatially-differentiated instrument, therefore $k^{min}_A < 0$. Consequently, merely negative cumulative environmental effects potentially reduce the welfare differential between the two instrument designs, i.e. $k < 0$, while positive cumulative environmental effects exacerbate the welfare differential – independent of their level. This is graphically depicted in figure 2. The blue graph represents the welfare differential $\Delta SC_{NW,HE}$ depending on the level of cumulative environmental effects, k. It is increasing in $k > 0$ and decreasing in $k < 0$ as long as $k^0 < k < 0$.

That is, whenever cumulative environmental effects exceed the level k^0, the welfare differential is higher than in the absence of cumulative environmental effects. The orange line represents this by capturing the level of the welfare differential for cumulative environmental effects of the size $k = k^0$ and $k = 0$.

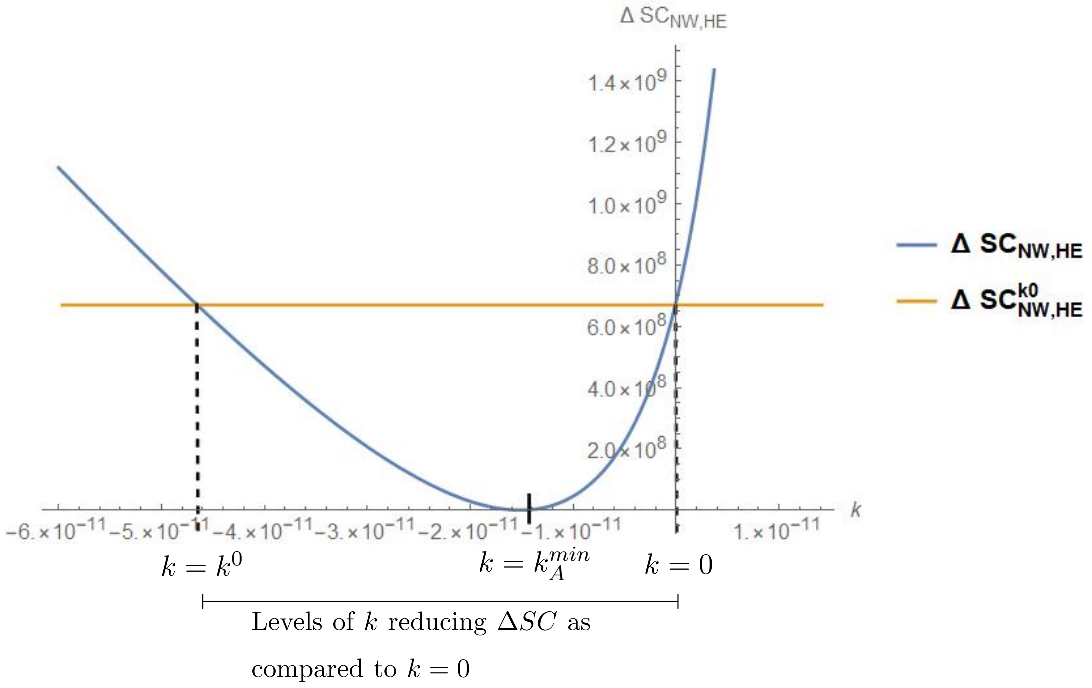

Figure 2: Level of the welfare differential ΔSC between a spatially-uniform and a spatially-differentiated regulation based on the level of cumulative environmental effects k for the neighbouring states Northrhine Westfalia (NW) and Hessia (HE), $k_A^{min} = -1.51 \cdot 10^{-11}$, $k^0 = -4.69 \cdot 10^{-11}$, $\Delta SC|_{k=k_0} = 6,82 \cdot 10^8$.

The opposite is true for states Thuringia (TH) and Bavaria (BY), depicted in figure 3. As the previous state combination, this state pair represents case A: For both instrument design types, more electricity is produced in Thuringia, $\frac{x^U_{TH}}{x^U_{BY}}, \frac{x^*_{TH}}{x^*_{BY}} > 1$. Yet, the concentration of electricity generation in Thuringia is more pronounced for a spatially-uniform than for a spatially-differentiated instrument, $\frac{x^*_{TH}}{x^*_{BY}} < \frac{x^U_{NW}}{x^U_{HE}}$. Positive cumulative environmental effects reinforce the concentration of electricity generation in Thuringia under a spatially-differentiated instrument, such that $k_A^{min} > 0$. Thus, only $k > 0$ may decrease the welfare differential between the two regulatory designs. However, when positive cumulative environmental effects exceed k^0, the welfare differential increases again. Therefore, cumulative environmental effects $0 < k < k^0$ reduce the welfare differential between a spatially-differentiated and uniform regulation, while $k < 0$ and $k > k^0$ result in an increase of the welfare differential.

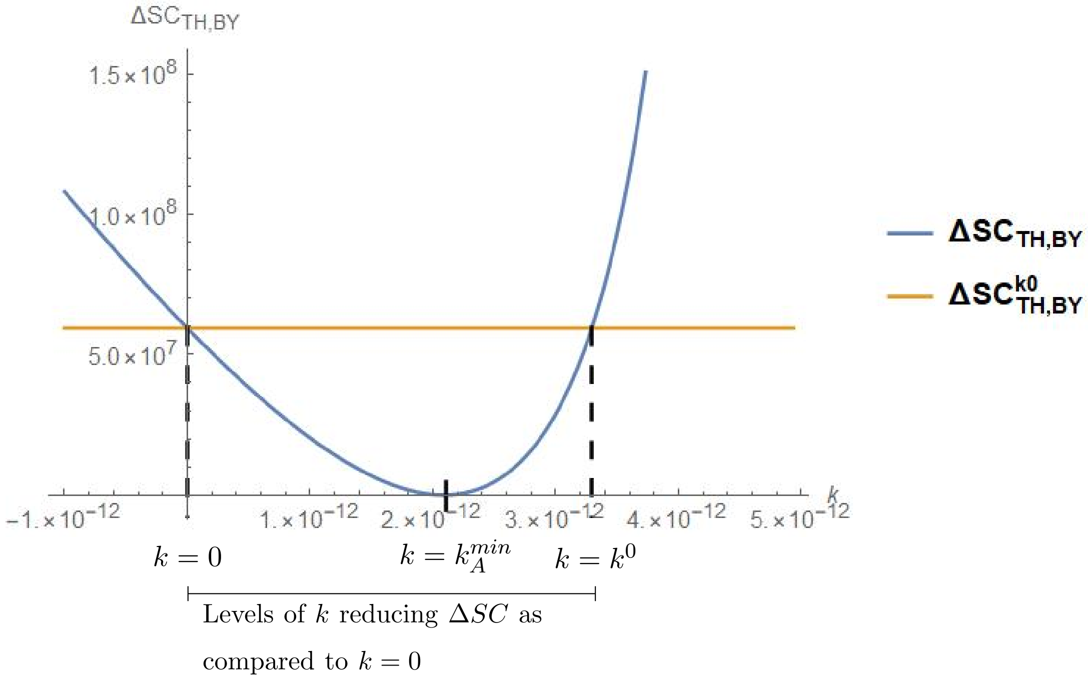

Figure 3: Level of the welfare differential ΔSC between a spatially-uniform and a spatially-differentiated regulation based on the level of cumulative environmental effects k for the neighbouring states Thuringia (TH) and Bavaria (BY), $k_A^{min} = 2.09 \cdot 10^{-12}$, $k^0 = 3.29 \cdot 10^{-12}$, $\Delta SC|_{k=k_0,k=0} = 5,95 \cdot 10^7$.

To gain insights into the relative level of the parameters k^{min} and k^0 as compared to region-specific environmental damages, the ratios $\frac{k^{min}}{d_i}$, $\frac{k^{min}}{d_j}$ and $\frac{k^0}{d_i}$, $\frac{k^0}{d_j}$ are calculated for each pair of neighbouring states considered (see columns six and seven of table 2). The results are displayed graphically in figure 4. Black and blue lines correspond to black and blue states of the respective state pair. The background of case B state pairs is tinted in grey. Ratios $\frac{k^0}{d_i}$ and $\frac{k^0}{d_j}$ are represented by dots. Each line in table 4 represents the range of cumulative environmental effects k that reduce the welfare differential between a spatially-differentiated and a uniform regulation as compared to the case $k = 0$.

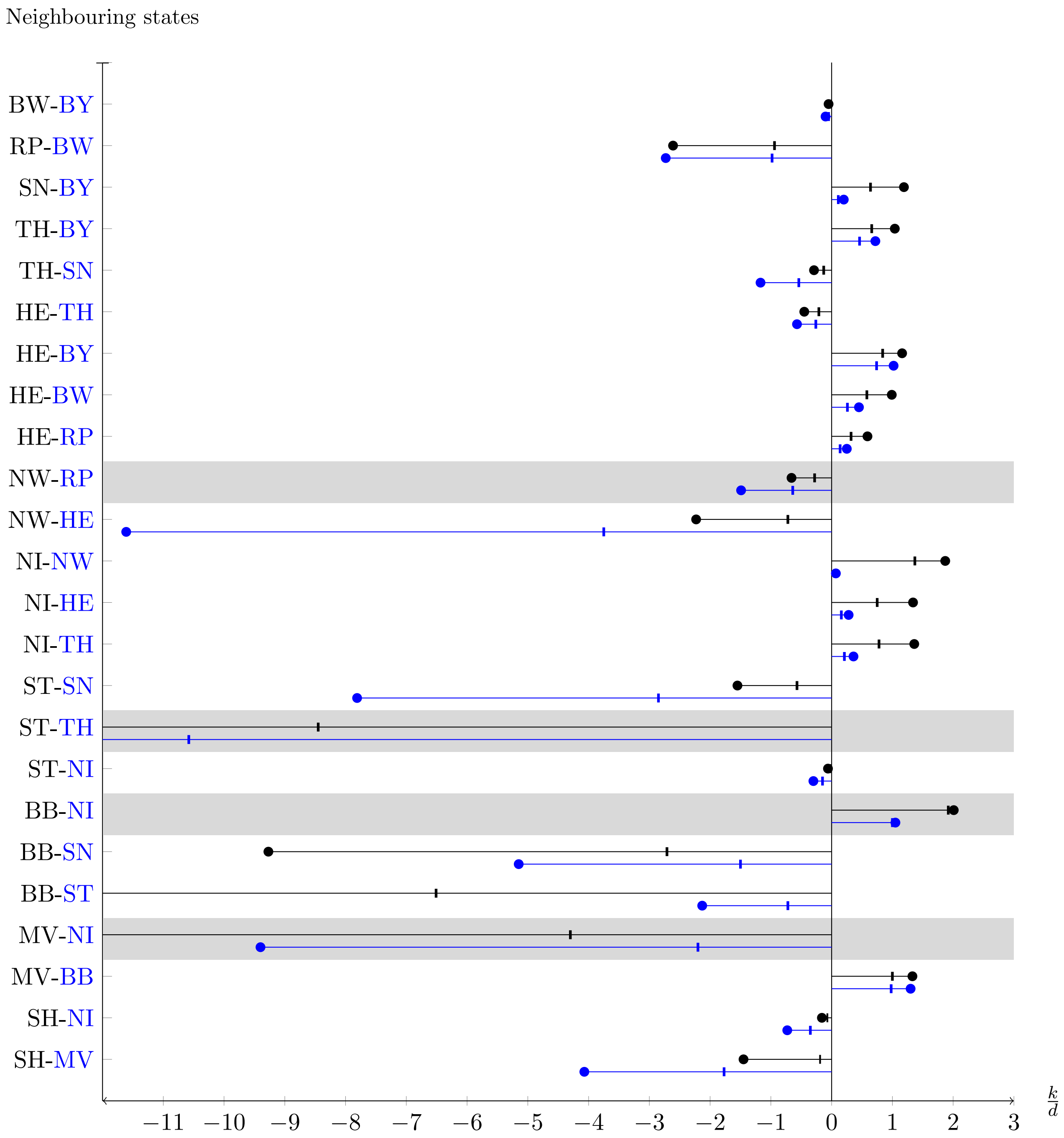

Figure 4: Ratio of different levels of cumulative environmental effects and state-specific environmental damages for neighbouring federal states in Germany. Dots mark $\frac{k^0}{d_i}$, $\frac{k^0}{d_j}$ while dashes represent $\frac{k^{min}}{d_i}$, $\frac{k^{min}}{d_j}$. Lines represent the level of cumulative environmental effects relative to region-specific environmental damagas that results in a welfare differential that is as high as or lower than in the absence of cumulative environmental effects, $k = 0$. Background tinted white for case A state pairs and grey for case B state pairs. Ratios not represented in the figure due to scaling reasons: MV–NI $\frac{k^0}{d_{MV}} = -18,40$, BB–ST $\frac{k^0}{d_{BB}} = -19,38$, ST – TH $\frac{k^0}{d_{ST}} = -79,36$ $\frac{k^0}{d_{TH}} = -99,34$.

As the length of the lines indicate, this range varies significantly between the state pairs. The dash on the lines represent $\frac{k^{min}}{d_i}$, $\frac{k^{min}}{d_j}$, i.e. the level of relative cumulative environmental effects that minimizes the welfare differential between the two regulatory designs. Overall, small ranges of cumulative environmental effects that reduce the welfare differential are characterized by relatively low levels of $\frac{k^{min}}{d_i}$, $\frac{k^{min}}{d_j}$ and vice versa. Therefore, in some cases cumulative environmental effects that are weak in comparison to environmental damages from regional electricity generation fully offset the welfare gains from spatially differentiating regulation. However, in these cases the range of cumulative environmental effects that actually reduce the welfare differential is small as well. This is for example the case in states Hessia (HE) and Rhineland Palatinite (RP). Cumulative environmental effects that amount to only 0.3 times the environmental damage parameter in Hessia or 0.1 times the environmental damage parameter in Rhineland Palatinite suffice to offset the welfare gains from a spatially-differentiated instrument. However, if cumulative environmental effects are larger than 0.6 times the environmental damage parameter in Hessia or than 0.25 times the environmental damage parameter in Rhineland Palatinite, they cause an increase in the welfare differential as compared to $k = 0$.

In contrast, for some state pairs relatively large cumulative environmental effects are needed to minimize the welfare gains from a spatially-differentiated as compared to a uniform instrument. This is the case in Brandenburg (BB) and Saxony (SN), where cumulative environmental effects equal to 2.7 times the environmental damage parameter in Brandenburg or 1.5 times the damage parameter in Saxony are needed to minimize the welfare gains from a spatially-differentiated regulation. On the other hand, the range of cumulative environmental effects that result in a decrease of the welfare differential is relatively high for these states. In Brandenburg and Saxony, cumulative environmental effects of up to 9.3 times the damage parameter in Brandenburg or 5.2 times the environmental damage parameter in Saxony reduce the welfare gains from a spatially-differentiated regulation. In general, figure 4 illustrates that the range of cumulative environmental effects that reduces or even minimizes the welfare gains from a spatially-differentiated as compared to a spatially-uniform instrument differs considerably between the state pairs and therefore highly depends on the state pair of interest.

Overall, the calibration confirmes the results from the theoretical model for the example of onshore wind power deployment across the German federal states. Cumulative environmental effects impact the welfare differential between a spatially-differentiated and a uniform regulation. Thus, the welfare differential may be reduced or even offset due to presence of cumulative effects. However, in order to assess whether this is actually the case, knowledge about the sign and size of cumulative environmental effects as well as about the values k^{min} and k^0 is essential. The state pairs displayed considerable differences regarding these values. For some state pairs, rather large cumulative environmental effects are required to minimize the welfare differential between a spatially-differentiated and uniform regulation. In these cases, the range of cumulative environmental effects that reduce the welfare differential is quite large as well. On the contrary, for other state pairs rather weak cumulative effects suffice to minimize the welfare gains from spatially differentiating regulation. The range of cumulative environmental effects that decrease the welfare differential between the two regulatory designs is then equally small. Clearly, if the above mentioned conditions for cumulative environmental effects are not met, their presence may also enhance the benefits from spatially-differentiating instrument design.

6 Discussion

The findings from the theoretical model show that efficient regulation for RES deployment is spatially-differentiated in the presence of both spatially-heterogeneous and cumulative environmental effects from RES electricity generation. Thus, we confirm the results regarding the optimal regulation of spatially heterogeneous environmental externalities found by the previous literature (Tietenberg, 1995; Kolstad, 1987; Waetzold and Drechsler, 2005). We further expand the framework to the additional presence of cumulative environmental effects. If ex ante the regulator is incompletely informed about generation costs, environmental damages or cumulative effects, a spatially-uniform instrument may turn out to be more efficient than a spatially-differentiated regulation ex post (Fowlie and Muller, 2019). However, this possibility does not alter the ex-ante policy decision.

Our findings extend the existing literature by indicating that understanding the characteristics of cumulative environmental effects is essential for the efficient design of a spatially-differentiated instrument. The welfare gains from spatially-differentiating instrument design may be altered substantially by the existence of cumulative effects on the environment. This is confirmed by the results from the numerical calibration. If cumulative effects on the environment are neglected, the welfare gains from spatially-differentiating instrument design already fluctuate considerably, depending on the state pair of interest. This fluctuation is based on the spatial heterogeneity of generation cost and environmental damage parameters. Taking cumulative effects on the environment into account can further reduce or increase the welfare differential, depending on the sign and size of cumulative environmental effects. For example, for the state pair Hessia (HE) and North Rhine-Westphalia (NW) the welfare differential between a spatially-differentiated and a uniform instrument may be offset completely (for $k = k_A^{min} = -1.5 \cdot 10^{-11}$) or doubled (for $k = 3.6 \cdot 10^{-12}$) by the presence of cumulative environmental effects. Thus, understanding cumulative effects on the environment that arise in the course of RES electricity generation matters for optimal spatially-differentiated instrument design.

Our analysis reveals that to determine how cumulative environmental effects impact the welfare differential between a spatially-differentiated and a uniform instrument design, three types of information are relevant. First, the regulator needs to be informed about the spatial heterogeneity of generation cost and environmental damage parameters. Only based on this knowledge, it is possible to derive the regional concentration of electricity generation for a spatially-differentiated and spatially-uniform instrument in the absence of cumulative environmental effects, and thus the sign and size of the value of cumulative effects for which the welfare differential is minimal k^{min}. Regarding generation costs of RES electricity, the regulator's information status can be assumed to be rather high, since these costs predominantly arise from site-specific natural conditions for which data is mostly available and accessible (e.g. wind yield or solar radiation). However, region-specific environmental damage parameters are contingent on local or regional characteristics for which data is less complete or available, depending on the environmental effect of interest. Nevertheless, the regulator may be able to observe if environmental damages from RES electricity generation in one region are higher or lower than in another region. For example, if a wind turbine is sited in a high-quality habitat for a wind power sensitive bird species, it most likely causes higher damages to the regional bird population than if sited in a low-quality habitat. With this information, the regulator can deduce the sign of k^{min}. Yet, to also draw conclusions on the size of k^{min}, information about the difference between region-specific damage parameters is needed. If available at all, this information is more complex to collect.

Second, the regulator must be able to observe the sign of actual cumulative environmental effects k. This knowledge is needed to determine whether cumulative effects pronounce (if k and k^{min} display different signs) or potentially reduce (if the signs are identical) the welfare differential between a spatially-differentiated and uniform instrument. Since cumulative environmental effects from interregional RES deployment are only recently gaining in importance, information on these effects is scarce. However, depending on the environmental impact of interest, first observations reveal some insight on the direction of cumulative environmental effects. For example, regarding the impact of onshore wind turbines on wind power sensitive bird species, cumulative environmental effects reflect the impact of deploying wind power in several regions that occurs in addition to region-specific impacts (Schaub, 2012; Drewitt and Langston, 2006; Gill et al., 2001). In this case, cumulative effects would have a positive sign $k > 0$ since interregional wind power deployment negatively affects aggregate damages from wind power generation to wind power sensitive bird populations.

Third, to determine the impact of cumulative environmental effects on the welfare deficit of a spatially-uniform instrument, information on both, the level of cumulative environmental effects and the value of k^0 is essential. This knowledge is needed to specify if cumulative environmental effects increase (if $|k| > |k^0|$) or reduce (if $|k| < |k^0|$) the welfare deficit of a spatially-uniform instrument design. It can be assumed that these are the most challenging informational requirements. Measuring cumulative environmental effects implies collecting data at an interregional scale. This is a challenging task, since both the complexity of collecting the data and the number and type of stakeholders involved in the data collection process are likely to increase with scale (Masden et al., 2010; Dahl et al., 2012; Schaub, 2012; May et al., 2019). To determine the value of k^0, the regulator needs to be perfectly informed about generation cost and environmental damage parameters. As argued above, this might be reasonable to assume for generation costs. However, information or uncertainty regarding environmental damage parameters is most likely incomplete.

Overall, informational requirements to design a spatially-differentiated instrument and to assess the impact of cumulative environmental effects on the welfare differential between a spatially-differentiated and a uniform regulation are high. Thus, while a spatially-differentiated instrument reaches the socially optimal allocation of electricity generation across regions in theory, the welfare gains associated with the spatial differentiation of instrument design may be reduced or offset by corresponding higher transaction costs in practice (Lehmann, 2012; Coggan et al., 2010). These include costs of collecting information on regional environmental damage parameters and cumulative effects as well as costs of administration and implementation of a spatially-differentiated instrument. The level of these transaction costs will depend on the spatial detail of the regulation and on the number of governmental levels included in the policy process (Coggan et al., 2010). If the welfare gains of a spatially-differentiated instrument do not outweigh the transaction costs associated with this type of regulation, a spatially-uniform instrument may be the rational policy choice.

Finally, calibration results indicate that the potential welfare gains from a spatially-differentiated instrument highly depend on the regions regulated. This is based on the fact that the level of and the heterogeneity in generation costs and environmental damages are rather context specific. Combined with the informational requirements for the decision on a spatially-uniform or differentiated instrument, this supports the inclusion of regional government levels into the regulatory decision-making process. Thereby, regional knowledge on heterogeneous generation cost and environmental damage parameters can be exploited.

The above described results rest upon several assumptions that are worth discussing. We use the standard assumption of increasing marginal generation costs $\frac{\partial^2 C_i(x_i)}{\partial x_i^2} > 0$ to reflect the spatial heterogeneity of relevant natural conditions for RES electricity generation (e.g. wind speed or solar radiation) within regions. Because a profit maximizing electricity producer will draw on sites with lowest marginal generation costs (and thus with most favourable natural conditions) first, marginal generation costs increase with electricity generation. It is arguable that if regions are small enough, natural conditions for RES electricity generation might not differ significantly between sites, such that marginal generation costs within regions are constant $\frac{\partial^2 C_i(x_i)}{\partial x_i^2} = 0$. In this case, the presence of cumulative environmental effects may be irrelevant for the welfare outcome of a spatially-uniform or spatially-differentiated instrument. This case applies if environmental damages caused by regional electricity generation are linear as well $\frac{\partial^2 D_(x_i)}{\partial x_i^2} = 0$ and if, in addition, cumulative environmental effects are positive $k > 0$. If both generation costs and regional environmental damages are linear, a spatially-uniform and a spatially-differentiated instrument result in the concentration of electricity generation in one region only (though not necessarily in the same region, depending on the spatial distribution of generation costs and environmental damage parameters). Positive cumulative environmental effects $k > 0$ merely increase environmental damages if generation takes place in more than one region. Therefore, regional electricity generation is unaltered by the presence of cumulative environmental effects for both a spatially-differentiated and a uniform instrument. If cumulative environmental effects are negative $k < 0$ instead, electricity generation in both regions may reduce the social costs of electricity generation. Therefore, they can affect the welfare differential between a spatially-uniform and spatially-differentiated instrument.

Regarding environmental damages, we assume increasing marginal damages per kWh of regional RES electricity generation $\frac{\partial^2 D(x_i)}{\partial x_i^2} > 0$. As argued in section 2, similar to the case of generation costs, the level of environmental damages of RES electricity generation is not equal for each production site. Instead, it varies with site-specific characteristics, e.g. for wind power plants onshore this might refer to their proximity to residential areas or to the type of bird or bat habitat they are located in. From an environmental damages perspective it is rational to use sites with lower environmental damages first and expand to sites with higher environmental damages in the course of expanding regional RES electricity generation. Therefore, marginal environmental damages from regional electricity generation are assumed to be increasing. If marginal environmental damages are decreasing in regional electricity generation $\frac{\partial^2 D(x_i)}{\partial x_i^2} < 0$, they favour electricity generation in the region with lower environmental damage parameters *only*. If generation costs are increasing they call for electricity generation in both regions instead. The impact of cumulative environmental effects in this setup depends on various model parameters, including the spatial distribution of generation cost and environmental damage parameters as well as the generation target $\bar{X}$.

The existence of cumulative environmental effects suggests that aggregate environmental damages caused by interregional RES development are higher or lower than the sum of environmental damages from region-specific electricity generation. We chose the most basic way to model this property of aggregate environmental damages by adding the product of regional electricity generation levels weighted by a cumulative environmental impact factor k to the sum of regional environmental damages $D(x_i, x_j) = \frac{d_i}{2}x_i^2 + \frac{d_j}{2}x_j^2 + kx_ix_j$. Positive (negative) values of k imply that aggregate environmental damages are increased (reduced) by electricity generation in both regions. Waetzold and Drechsler (2005) model cumulative benefits from biodiversity-enhancing land-use measures by multiplying regional benefits $B_{tot} = B_1B_2$. However, this suggests that aggregate benefits are only positive if biodiversity-enhancing land-use measures are implemented in both regions. If they take place in one region only, then aggregate benefits are zero. If aggregate environmental damages in our model would be represented by the product of regional environmental damages, then damages would be minimized (equal to zero) if generation was concentrated in one region only, independently of the level of environmental damages in this region. This suggests that, from an environmental damages perspective, it would be as beneficial to allocate all electricity generation to the region with higher environmental damages as to the region with lower environmental damages. This hypothesis seems rather unlikely for the case of environmental damages from RES electricity generation.

Our model is characterized by a cost-minimization framework. This is a realistic set up because many countries draw on quantity or percentage targets for RES development in the course of transitioning electricity generation from conventional to renewable resources (IRENA, 2020). We analyse how these targets can be met at minimal social cost of renewable electricity generation. We thus suggest that RES electricity generation targets are exogenously defined, e.g. by political decision-makers. However, this assumption neglects the fact that the socially optimal aggregate level of electricity generation could be determined endogenously by weighing the costs and benefits (e.g. greenhouse gas emissions reductions) of RES deployment. In this case, aggregate electricity generation may differ between a spatially-differentiated and spatially-uniform instrument. Because a uniform regulation remains inefficient in the presence of spatially-heterogeneous environmental externalities, RES deployment with this instrument design results in higher social costs. Thus, the corresponding aggregate level of electricity generation will be lower than with a spatially-differentiated regulation. Furthermore, the level of a uniform subsidy in a cost-benefit framework depends on environmental damage parameters and cumulative effects in addition to generation cost parameters. Assessing the impact of cumulative environmental effects on the welfare differential between the two regulatory designs in this setup is more complex and should be conducted in a separate analysis.

Finally, the model is limited by the number of regions and environmental externalities considered. RES development certainly takes place in more than two regions. In the model, this can be reflected by including n regions, with n representing any positive integer. Similarly, it may be assumed that RES electricity generation causes multiple environmental externalities that are relevant at a spatial scale (Zerrahn, 2017). More externalities might be accompanied by additional cumulative effects on the environment. Furthermore, increased deployment of RES in the electricity sector entails additional costs to the power system, such as expenses linked to the provision of distribution or transmission networks or balancing services. These system integration costs emerge on top of RES electricity generation costs and may also feature spatial components (Hirth et al., 2015). Besides, grid infrastructure is often associated with environmental externalities as well (Devine-Wright and Batel, 2013; Pérez-García et al., 2017). Considering these additional regions, externalities and system elements is important, yet, it also complicates the analysis by adding to the spatial components determining the optimal allocation of RES electricity generation infrastructure across regions. Thus, designing a socially-optimal spatially-differentiated instrument is even more challenging in practice. Potential transaction or administrative costs associated with a spatially-differentiated instrument are likely to increase, such that the welfare gains of a spatially-differentiated instrument as opposed to a spatially-uniform regulation are even more difficult to determine.

7 Conclusion

The expansion of electricity generation from renewable energy sources (RES) is vital for the achievement of climate targets, such as the aims of the Paris Agreement. Especially wind power onshore and open-space photovoltaic systems are main contributors to electricity generation from RES. However, these technologies are also associated with local or regional environmental externalities. The level of these externalities differs between regions or locations. Moreover, these externalities may be subject to interregional cumulative effects. That is, marginal environmental damages from regional electricity generation also depend on electricity generation in another region. As a result, aggregate environmental damages from RES electricity generation are higher or lower than the sum of environmental damages from regional electricity generation. Based on these environmental effects from RES deployment, we compare the outcomes of a spatially-differentiated and spatially-uniform policy to govern the deployment of RES electricity generation. We assessed the welfare differential between the two regulatory designs, and how the presence of cumulative environmental effects alters it both, theoretically and by employing a numerical example.

The results of our model indicate that in the presence of cumulative environmental effects and spatially-heterogeneous environmental damages, a spatially-differentiated instrument design always welfare-dominates a spatially-uniform regulation. To optimally design a spatially-differentiated policy, it is essential to understand the characteristics of cumulative environmental effects.

The presence of cumulative environmental effects may both increase or reduce the welfare differential between a spatially-differentiated and a uniform regulation. This depends on the regional distribution of generation cost parameters and social cost parameters of electricity generation and on the sign and size of cumulative effects. If the heterogeneity in generation cost parameters is stronger (weaker) than in social cost parameters, positive (negative) cumulative environmental effects may decrease the welfare differential of a spatially-uniform instrument. However, negative (positive) cumulative effects raise the welfare differential.

While a spatially-differentiated instrument can implement the socially-optimal regional allocation of RES electricity generation, it is usually associated with higher transaction costs, such as administrative or informational burdens, than a spatially-uniform instrument. If the presence of cumulative environmental effects reduces the welfare deficit of a spatially-uniform instrument sufficiently, it may be optimal to implement the uniform instrument instead. However, to assess whether this is the case, the regulator needs to be informed about the heterogeneity in generation costs and regional environmental damages as well as about the sign and size of cumulative environmental effects. Nevertheless, if the regulator possesses this knowledge, administrative hurdles of implementing a spatially-differentiated instrument might diminish.

These high informational requirements for optimal policy design might reveal avenues for future research. Although the deployment of RES has been proceeding for more than two decades in many European countries, the availability of data on the heterogeneity of region-specific environmental damages is still rather limited. The importance of cumulative environmental effects is a more recent topic due to the fact that these effects depend on and grow with the deployment of RES technologies across several regions. As a result, knowledge on cumulative effects on the environment is even more scarce. Therefore, analysing how uncertainty regarding region-specific environmental damages and cumulative effects shapes optimal instrument design can contribute to a more comprehensive understanding of the welfare implications of different regulatory choices for the deployment of RES technologies.

Appendix A Socially optimal spatial allocation of RES electricity generation

The first-best spatial allocation of electricity generation is determined by minimising the social costs of electricity generation subject to the generation target restriction $\bar{X}$:

$$\min_{x_i,x_j} SC = C_i(x_i) + C_j(x_j) + D(x_i, x_j) \qquad \text{s.t. } x_i + x_j \geq \bar{X},$$
$$x_i, x_j \geq 0$$

Since electricity generation in our framework is only associated with costs (generation costs and environmental damages), there is no incentive to generate more electricity than required by the target. Therefore, the quantity constraint for the generation target is binding. The corresponding Lagrangian is subsequently differentiated with respect to x_i, x_j and λ:

$$\mathcal{L} = \frac{c_i}{2}x_i^2 + \frac{c_j}{2}x_j^2 + \frac{d_i}{2}x_i^2 + \frac{d_j}{2}x_j^2 + kx_ix_j - \lambda\big(x_i + x_j - \bar{X}\big)$$
$$\frac{\partial\mathcal{L}}{\partial x_i} = (c_i + d_i)x_i + kx_j - \lambda \overset{!}{=} 0 \tag{32}$$
$$\frac{\partial\mathcal{L}}{\partial x_j} = (c_j + d_j)x_j + kx_i - \lambda \overset{!}{=} 0 \tag{33}$$
$$\frac{\partial\mathcal{L}}{\partial \lambda} = x_i + x_j - \bar{X} \overset{!}{=} 0 \tag{34}$$

Solving (32) and (33) for λ and equating them reaches:

$$(c_i + d_i)x_i + kx_j = (c_j + d_j)x_j + kx_i \tag{35}$$

In the social optimum, marginal social costs from RES electricity generation are equal across regions. Solving (35) for x_j and inserting into (34) delivers the socially optimal allocation levels x_i^*, x_j^* for an inner solution:

$$x_i^* = \frac{(c_j + d_j - k)\bar{X}}{(c_i + d_i + c_j + d_j - 2k)}, \qquad x_j^* = \frac{(c_i + d_i - k)\bar{X}}{(c_i + d_i + c_j + d_j - 2k)}$$

The bordered Hessian matrix for the optimization problem is represented by HL:

$$HL(\lambda^*, x_i^*, x_j^*) = \begin{pmatrix} c_i + d_i & k & -1 \\ k & c_j + d_j & -1 \\ -1 & -1 & 0 \end{pmatrix} \tag{36}$$

For the matrix, the partial derivatives of the Lagrange function are evaluated at the point (x_i^*, x_j^*) and λ^*. The allocation x_i^*, x_j^* represents a local minimum of the social welfare function (3) if:

$$- \, det(HL(\lambda^*, x_i^*, x_j^*)) > 0$$
$$- \, (k(-1)(-1) + (-1)k(-1) - (-1)(c_j + d_j)(-1) - (-1)(-1)(c_i + d_i)) > 0$$
$$- \, (2k - (c_j + d_) - (c_i + d_i)) > 0$$
$$2k - (c_i + d_i + c_j + d_j) < 0$$
$$k < \frac{c_i + d_i + c_j + d_j}{2} = \alpha$$

The spatial allocation of electricity generation x_i^*, x_j^* only represents a local minimum of the social cost function if cumulative effects are smaller than α. Otherwise, they mark a local maximum of the social cost function.
By further determining the sign of the leading principal minors of the Hessian, another restriction for k is identified:

$$\text{Second order leading principal minor:} \quad D_2 = \begin{vmatrix} (c_i + d_i) & k \\ k & (c_j + d_j) \end{vmatrix} =$$
$$= (c_i + d_i)(c_j + d_j) - k^2 > 0$$
$$-\underbrace{\sqrt{(c_i + d_i)(c_j + d_j)}}_{\beta} < k < \sqrt{(c_i + d_i)(c_j + d_j)} \tag{37}$$

$$\text{First-order leading principal minor:} \quad D_1 = \left|(c_i + d_i)\right| = (c_i + d_i) > 0$$

The first-order principal minor of the Hessian D_1 is always positive because $c_i, d_i > 0$. The second order principal minor D_2 is only positive if $-\beta < k < \beta$ (37).

Appendix B First-best spatially-differentiated subsidy

The first-best spatially-differentiated subsidy is derived by inserting $x_i(s_i), x_j(s_j)$ from (7) into the social cost function (4) and by subsequently minimizing with respect to s_i, s_j while considering the quantity restrictions:

$$\min_{s_i, s_j} SC = \frac{c_i}{2} \quad \frac{s_i}{c_i}^{\;2} + \frac{c_j}{2} \quad \frac{s_j}{c_j}^{\;2} + \frac{d_i}{2} \quad \frac{s_i}{c_i}^{\;2} + \frac{d_j}{2} \quad \frac{s_j}{c_j}^{\;2} + k \quad \frac{s_i}{c_i} \quad \frac{s_j}{c_j}$$
$$s.t. \quad \frac{s_i}{c_i} + \frac{s_j}{c_j} \geq \bar{X}$$
$$\frac{s_i}{c_i}, \frac{s_j}{c_j} \geq 0$$

The corresponding Lagrangian reads as follows:

$$\mathcal{L} = \frac{c_i}{2} \quad \frac{s_i}{c_i}^{\;2} + \frac{c_j}{2} \quad \frac{s_j}{c_j}^{\;2} + \frac{d_i}{2} \quad \frac{s_i}{c_i}^{\;2} + \frac{d_j}{2} \quad \frac{s_j}{c_j}^{\;2} + k \quad \frac{s_i}{c_i} \quad \frac{s_j}{c_j} - \lambda \quad \frac{s_i}{c_i} + \frac{s_j}{c_j} \quad - \bar{X}$$

$$\frac{\partial \mathcal{L}}{\partial s_i} = s_i \quad 1 + \frac{d_i}{c_i} \quad + s_j \frac{k}{c_j} - \lambda \stackrel{!}{=} 0 \tag{38}$$
$$\frac{\partial \mathcal{L}}{\partial s_j} = s_j \quad 1 + \frac{d_j}{c_j} \quad + s_i \frac{k}{c_i} - \lambda \stackrel{!}{=} 0 \tag{39}$$
$$\frac{\partial \mathcal{L}}{\partial \lambda} = \bar{X} - \frac{s_i}{c_i} - \frac{s_j}{c_j} \stackrel{!}{=} 0 \tag{40}$$

Solving (38) and (39) for λ and equating them delivers $s_j(s_i)$. Inserting $s_j(s_i)$ into (40) reaches the first-best spatially-differentiated subsidy levels:

$$s_i^* = \frac{\bar{X} c_i (c_j + d_j - k)}{(c_i + d_i + c_j + d_j - 2k)}, \qquad s_j^* = \frac{\bar{X} c_j (c_i + d_i - k)}{(c_i + d_i + c_j + d_j - 2k)} \qquad i = j$$

Appendix C Effect of cumulative environmental effects on the welfare differential between a spatially-uniform and spatially-differentiated subsidy

In the following, the impact of cumulative environmental effects k on the welfare differential between a spatially-uniform and a spatially-differentiated regulation is computed. First, the direct and indirect impacts of k on ΔSC are identified:

$$\Delta SC = SC^U - SC^* =$$
$$= \frac{c_i + d_i}{2} \; x_i^{U2} - \underbrace{x_i^*(k)^2}_{\text{Indirect effect region i}} + \frac{c_j + d_j}{2} \; x_j^{U2} - \underbrace{x_j^*(k)^2}_{\text{Indirect effect region j}} + \underbrace{k \;\; x_i^U x_j^U - x_i^*(k) x_j^*(k)}_{\text{Direct and indirect effect}} \tag{41}$$

The direct effect of k on the welfare costs of a uniform regulation is represented in the last multiplicative term of (41), while the indirect effect is present in every term via the quantities $x_i^*(k)$. The marginal effect of a change in k on ΔSC is derived by taking the total derivative of (41):

$$\frac{\partial \Delta SC}{\partial k} = -(c_i + d_i)(x_i^* \frac{\partial x_i^*}{\partial k}) - (c_j + d_j)(x_j^* \frac{\partial x_j^*}{\partial k}) + x_i^U x_j^U - x_i^* x_j^* - k(x_i^* \frac{\partial x_j^*}{\partial k} + x_j^* \frac{\partial x_i^*}{\partial k}) \tag{42}$$

Rearranging and substituting $\frac{\partial x_j^*}{\partial k} = -\frac{\partial x_i^*}{\partial k}$ reaches:

$$\frac{\partial \Delta SC}{\partial k} = -(c_i + d_i - k) x_i^* \frac{\partial x_i^*}{\partial k} + (c_j + d_j - k) x_j^* \frac{\partial x_i^*}{\partial k} + x_i^U x_j^U - x_i^* x_j^* \tag{43}$$

The first two additive terms in (43) offset each other, such that the impact of k on ΔSC is represented by the direct effect $(x_i^U x_j^U - x_i^* x_j^*)$ only. This can be seen more clearly by inserting x_i^*, x_j^* into (43):

$$\frac{\partial \Delta SC}{\partial k} = \underbrace{-\frac{k\bar{X}^2 (c_i + d_i - c_j - d_j)^2}{c_i + d_i + c_j + d_j - 2k)^3} + \frac{k\bar{X}^2 (c_i + d_i - c_j - d_j)^2}{c_i + d_i + c_j + d_j - 2k)^3}}_{=0}$$
$$\underbrace{+ \frac{c_i c_j \bar{X}^2}{(c_i + c_j)^2} - \frac{\bar{X}^2 (c_i + d_i - k)(c_j + d_j - k)}{(c_i + d_i + c_j + d_j - 2k)^2}}_{x_i^U x_j^U - x_i^* x_j^*} \tag{44}$$

Appendix D Calibrated model: Generation cost and environmental damage parameters per federal state

Federal state (abbreviation)	c_{1i} $i = 1, ..., 12$	c_{2i} $i = 1, ..., 12$	d_i $i = 1, ..., 12$
Baden-Wuerttemberg (BW)	$0,062$	$1,84705\ 10^{-12}$	$8,93010\ 10^{-12}$
Bavaria (BY)	$0,052$	$1,33494\ 10^{-12}$	$4,57779\ 10^{-12}$
Brandenburg (BB)	$0,046$	$2,70273\ 10^{-13}$	$4,37312\ 10^{-13}$
Hessia (HE)	$0,046$	$9,58190\ 10^{-13}$	$4,03977\ 10^{-12}$
Mecklenburg-Western Pomerania (MV)	$0,042$	$1,41837\ 10^{-13}$	$4,29472\ 10^{-13}$
Lower Saxony (NI)	$0,040$	$2,12205\ 10^{-13}$	$8,40227\ 10^{-13}$
North Rhine-Westphalia (NW)	$0,050$	$1,53183\ 10^{-12}$	$2,10787\ 10^{-11}$
Rhineland-Palatinate (RP)	$0,049$	$2,52251\ 10^{-12}$	$9,35231\ 10^{-12}$
Saxony (SN)	$0,049$	$1,69078\ 10^{-13}$	$7,87437\ 10^{-13}$
Saxony-Anhalt (ST)	$0,038$	$1,15154\ 10^{-12}$	$3,96975\ 10^{-12}$
Schleswig-Holstein (SH)	$0,041$	$6,75146\ 10^{-13}$	$3,91271\ 10^{-12}$
Thuringia (TH)	$0,046$	$7,8735\ 10^{-13}$	$3,17155\ 10^{-12}$

Table 3: Estimated coefficients for the generation cost function and the environmental damage cost function of onshore wind power deployment for the German federal states, except Berlin, Bremen, Hamburg and Saarland. Adapted from (Meier and Lehmann, 2020).

References

Agora Energiewende (2013). Kostenoptimaler Ausbau der Erneuerbaren Energien in Deutschland: Ein Vergleich möglicher Strategien für den Ausbau von Wind- und Solarenergie in Deutschland bis 2033.
https://static.agora-energiewende.de/fileadmin2/Projekte/2012/Kostenoptmaler-Ausbau-EE/Agora_Studie_Kostenoptimaler_Ausbau_der_EE_Web_optimiert.pdf. Last accessed: 2021/03/16

Ambec, S. and J. Coria (2013). Prices vs quantities with multiple pollutants. *Journal of Environmental Economics and Management 66*(1), 123–140.

Borenstein, S. (2012). The Private and Public Economics of Renewable Electricity Generation. *Journal of Economic Perspectives 26*(1), 67–92.

Botelho, A., L. Lourenço-Gomes, L. Pinto, S. Sousa, and M. Valente (2017). Accounting for local impacts of photovoltaic farms: The application of two stated preferences approaches to a case-study in Portugal. *Energy Policy 109*, 191–198.

Caplan, A. J. (2006). A Comparison of Emission Taxes and Permit Markets for Controlling Correlated Externalities. *Environmental and Resource Economics 34*(4), 471–492.

Coggan, A., S. M. Whitten, and J. Bennett (2010). Influences of transaction costs in environmental policy. *Ecological Economics 69*(9), 1777–1784.

Crago, C. L. and J. K. Stranlund (2015). Optimal regulation of carbon and co-pollutants with spatially differentiated damages. *mimeo*.
https://ageconsearch.umn.edu/record/205594/files/Crago%20Stranlund%20June%202015.pdf. Last accessed: 2021/03/16

Dahl, E. L., K. Bevanger, T. Nygård, E. Røskaft, and B. G. Stokke (2012). Reduced breeding success in white-tailed eagles at Smøla windfarm, western Norway, is caused by mortality and displacement. *Biological Conservation 145*(1), 79–85.

Dai, K., A. Bergot, C. Liang, W.-N. Xiang, and Z. Huang (2015). Environmental issues associated with wind energy – A review. *Renewable Energy 75*, 911–921.

del Río, P. (2017). Designing auctions for renewable electricity support. Best practices from around the world. *Energy for Sustainable Development 41*, 1–13.

Deutsche WindGuard GmbH (2020). Status des Windenergieausbaus an Land in Deutschland: Erstes Halbjahr 2020.
https://www.windguard.de/veroeffentlichungen.html?file=files/cto_layout/img/unternehmen/veroeffentlichungen/2020/Status%20des%20Windenergieausbaus%20an%20Land%20-%20Halbjahr%202020.pdf. Last accessed 2021/03/16

Devine-Wright, P. and S. Batel (2013). Explaining public preferences for high voltage pylon designs: An empirical study of perceived fit in a rural landscape. *Land Use Policy 31*, 640–649.

Drechsler, M., J. Egerer, M. Lange, F. Masurowski, J. Meyerhoff, and M. Oehlmann (2017). Efficient and equitable spatial allocation of renewable power plants at the country scale. *Nature Energy 2*(9), 17124.

Drewitt, A. L. and R. H. Langston (2006). Assessing the impacts of wind farms on birds. *Ibis 148*(s1), 29–42.

EEG 2021 (2021). Erneuerbare-Energien-Gesetz vom 21. Juli 2014 (BGBl. I S. 1066), das zuletzt durch Artikel 1 des Gesetzes vom 21. Dezember 2020 (BGBl. I S. 3138) geändert worden ist.

Evans, A., V. Strezov, and T. J. Evans (2009). Assessment of sustainability indicators for renewable energy technologies. *Renewable and Sustainable Energy Reviews 13*(5), 1082–1088.

Fehr, E., M. Naef, and K. M. Schmidt (2006). Inequality Aversion, Efficiency, and Maximin Preferences in Simple Distribution Experiments: Comment. *American Economic Review 96*(5), 1912–1917.

Fehr, E. and K. M. Schmidt (1999). A Theory of Fairness, Competition, and Cooperation. *The Quarterly Journal of Economics 114*(3), 817–868.

Fowlie, M. and N. Muller (2019). Market-Based Emissions Regulation When Damages Vary across Sources: What Are the Gains from Differentiation? *Journal of the Association of Environmental and Resource Economists 6*(3), 593–632.

Gill, J. A., K. Norris, and W. J. Sutherland (2001). Why behavioural responses may not reflect the population consequences of human disturbance. *Biological Conservation 97*(2), 265–268.

Hirth, L., F. Ueckerdt, and O. Edenhofer (2015). Integration costs revisited – An economic framework for wind and solar variability. *Renewable Energy 74*, 925–939.

Hötker, H., K.-M. Thomsen, and H. Jeromin (2006). *Impacts on biodiversity of exploitation of renewable energy sources: the example of birds and bats: Facts, gaps in knowledge, demands for further research, and onithological guidelines for the development of renewabe energy exploitation.* Bergenhusen.

IRENA (2020). *Global Renewables Outlook: Energy transformation 2050: (Edition: 2020).* International Renewable Energy Agency. Abu Dhabi. `https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_Global_Renewables_Outlook_2020.pdf`. Last accessed:2021/03/16

Jenkins, K., D. McCauley, R. Heffron, H. Stephan, and R. Rehner (2016). Energy justice: A conceptual review. *Energy Research & Social Science 11*, 174–182.

Kolstad, C. D. (1987). Uniformity versus differentiation in regulating externalities. *Journal of Environmental Economics and Management 14*(4), 386–399.

Kost, C., S. Shammugam, V. Jülch, H.-T. Nguyen, and T. Schlegl (2018). Studie: Stromgestehungskosten Erneuerbare Energien. *Fraunhofer-Institut für Solare Energiesysteme ISE*. https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/DE2018_ISE_Studie_Stromgestehungskosten_Erneuerbare_Energien.pdf. Last accessed: 2021/02/26

Langer, K., T. Decker, J. Roosen, and K. Menrad (2016). A qualitative analysis to understand the acceptance of wind energy in Bavaria. *Renewable and Sustainable Energy Reviews 64*, 248–259.

Lehmann, P. (2012). Justifying A Policy Mix For Pollution Control: A Review Of Economic Literature. *Journal of Economic Surveys 26*(1), 71–97.

Lehmann, P. (2013). Supplementing an emissions tax by a feed-in tariff for renewable electricity to address learning spillovers. *Energy Policy 61*, 635–641.

Lehmann, P., K. Ammermann, E. Gawel, C. Geiger, J. Hauck, J. Heilmann, J.-N. Meier, J. Ponitka, S. Schicketanz, B. Stemmer, P. Tafarte, D. Thrän, and E. Wolfram (2020). Managing spatial sustainability trade-offs: The case of wind power. *UFZ Discussion Papers* (No. 4/2020).

Masden, E. A., A. D. Fox, R. W. Furness, R. Bullman, and D. T. Haydon (2010). Cumulative impact assessments and bird-wind farm interactions: Developing a conceptual framework. *Environmental Impact Assessment Review 30*(1), 1–7.

Masurowski, F., M. Drechsler, and K. Frank (2016). A spatially explicit assessment of the wind energy potential in response to an increased distance between wind turbines and settlements in Germany. *Energy Policy 97*, 343–350.

Mattmann, M., I. Logar, and R. Brouwer (2016). Wind power externalities: A meta-analysis. *Ecological Economics 127*, 23–36.

May, R., E. A. Masden, F. Bennet, and M. Perron (2019). Considerations for upscaling individual effects of wind energy development towards population-level impacts on wildlife. *Journal of environmental management 230*, 84–93.

Meier, J.-N. and P. Lehmann (2020). Optimal federal co-regulation of renewable energy deployment. *UFZ Discussion Papers* (8/2020).

Meyerhoff, J., C. Ohl, and V. Hartje (2010). Landscape externalities from onshore wind power. *Energy Policy 38*(1), 82–92.

Molnarova, K., P. Sklenicka, J. Stiborek, K. Svobodova, and M. Salek (2012). Visual preferences for wind turbines: Location, numbers and respondent characteristics. *Applied Energy 92*, 269–278.

Moslener, U. and T. Requate (2007). Optimal abatement in dynamic multi-pollutant problems when pollutants can be complements or substitutes. *Journal of Economic Dynamics and Control 31*(7), 2293–2316.

Pérez-García, J. M., T. L. DeVault, F. Botella, and J. A. Sánchez-Zapata (2017). Using risk prediction models and species sensitivity maps for large-scale identification of infrastructure-related wildlife protection areas: The case of bird electrocution. *Biological Conservation 210*, 334–342.

Sasse, J.-P. and E. Trutnevyte (2019). Distributional trade-offs between regionally equitable and cost-efficient allocation of renewable electricity generation. *Applied Energy 254*, 113724.

Schaub, M. (2012). Spatial distribution of wind turbines is crucial for the survival of red kite populations. *Biological Conservation 155*, 111–118.

Schuster, E., L. Bulling, and J. Köppel (2015). Consolidating the State of Knowledge: A Synoptical Review of Wind Energy's Wildlife Effects. *Environmental management 56*(2), 300–331.

Sims, R. E., H.-H. Rogner, and K. Gregory (2003). Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. *Energy Policy 31*(13), 1315–1326.

Stranlund, J. K. and I. Son (2019). Prices Versus Quantities Versus Hybrids in the Presence of Co-pollutants. *Environmental and Resource Economics 73*(2), 353–384.

Tafarte, P. and P. Lehmann (2019). Trade-Offs associated with the spatial allocation of future onshore wind generation capacity – a case study for Germany. *Proceedings of the 16th International Conference on the European Energy Market (EEM).*

Tietenberg, T. (1978). Spatially differentiated air pollutant emission charges: An Economic and Legal Analysis. *Land Economics 54*(3), 265–277.

Tietenberg, T. H. (1995). Tradeable Permits for Pollution Control when Emission Location Matters: What have We Learned? *Environmental and Resource Economics 5*(2), 95–113.

Tsoutsos, T., N. Frantzeskaki, and V. Gekas (2005). Environmental impacts from the solar energy technologies. *Energy Policy 33*(3), 289–296.

Ueckerdt, F., L. Hirth, G. Luderer, and O. Edenhofer (2013). System LCOE: What are the costs of variable renewables? *Energy 63*, 61–75.

Waetzold, F. and M. Drechsler (2005). Spatially Uniform versus Spatially Heterogeneous Compensation Payments for Biodiversity-Enhancing Land-Use Measures. *Environmental & Resource Economics 31*(1), 73–93.

Zerrahn, A. (2017). Wind Power and Externalities. *Ecological Economics 141*, 245–260.