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# Handling uncertainty in bioenergy policy design – A case study analysis of UK and German bioelectricity policy instruments

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ABSTRACT

In designing policies to promote bioenergy, policy makers face challenges concerning uncertainties about the sustainability of bioenergy pathways (including greenhouse gas balances), technology and resource costs, or future energy market framework conditions. New information becomes available with time, but policy adjustments can involve high levels of adaptation costs. To enable an effective steering of technology choices and innovation, policies have to strike a balance between creating a consistent institutional framework, which establishes planning security for investors, and sufficient flexibility to adapt to new information. This paper examines implications of economic theory for handling cost and benefit uncertainty in bioelectricity policy design, focussing on choices between price and quantity instruments, technology differentiation, and policy adjustment. Findings are applied to two case studies, the UK's Renewables Obligation and the German feed-in tariff/feed-in premium scheme. Case study results show the trade-offs that are involved in instrument choice and design – depending on political priorities and a country's specific context, different options can prove more adequate. Combining market-based remuneration with sustainability criteria results in strong incentives for bioenergy producers to search for low-cost solutions; whereas cost-based price instruments with centrally steered technology and feedstock choices offer higher planning security for investors and more direct control for policy makers over what pathways are implemented. Independent of the choice of instrument type and technology differentiation mechanism, findings emphasise the importance of a careful policy design, which determines the exact balance between performance criteria such as cost control, incentive intensity, planning security and adaptive efficiency.



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## 1. Introduction

Bioenergy use in the electricity sector plays an important role in meeting renewable energy expansion and greenhouse gas (GHG) mitigation targets in many EU member states [1]. Due to a lack of commercial competitiveness with fossil fuel-based technologies, the uptake of bioelectricity technologies relies heavily on policy incentives. From an economics perspective, the rationale for policy intervention on behalf of bioenergy lies in the correction of market failures. For one, negative GHG externalities of fossil fuels distort competition with renewable energy sources (RES). Furthermore, bioenergy can make a positive contribution to the public good "secure energy supply" [2], by substituting fossil fuel imports from geopolitically instable regions [3], or by providing systemic benefits in an electricity system with high shares of volatile RES, where bioenergy can act as a renewable option for balancing fluctuations [4]. At the same time, investments in innovative technologies and learning generate knowledge spillovers as positive externalities. The existence of multiple market failures justifies the use of a policy mix combining instruments like the European Emissions Trading System (EU ETS), which sets a price on GHG emissions, and direct support instruments aimed at promoting RES diffusion, like renewable quotas or feed-in tariffs [5,6]. To ensure an effective innovation system for low carbon technologies, demand-pull measures such as these need to be further combined with instruments promoting the supply of innovative technologies and knowledge creation, such as research and development support [7–10]. Functioning knowledge exchange networks and economic and political framework conditions which are conducive to innovation are further elements of effective innovation systems [7,8]. The focus of policy interventions, meanwhile, needs to be aligned with a technology's stage of commercial maturity. For bioenergy use in the electricity sector, deployment support is of particular relevance, because major technologies such as biogas and solid biofuel-based combined heat and power (CHP) production have reached a comparatively high level of technological maturity, even though potentials for incremental innovation remain [11,12]. The EU ETS as an indirect support instrument fails to create a level playing field for competition with conventional energy technologies, which benefit from economies of scale, past learning effects and persistently low levels of emission allowance prices [13,14]. Moreover, current market framework conditions set only limited incentives for the provision of flexible capacities, even though their systemic importance is growing as shares of volatile RES increase [15–17]. In this context, direct deployment support is necessary to further develop bioenergy technologies as part of a diverse RES portfolio, and reflect bioenergy's option value as a dispatchable, low-carbon RES in the future electricity mix.

Meanwhile, the heterogeneity of technology–feedstock combinations and associated environmental and socio-economic impacts makes it a difficult task to design policy instruments which incentivise cost-effective contributions of bioenergy to RES and GHG mitigation targets while also ensuring the sustainability of developments [18]. Particularly problematic for bioenergy policy design is the pervasive existence of uncertainty about the costs and benefits of various pathways. While uncertainty about the private cost characteristics of RES plants and future learning curve effects is a well-researched phenomenon [19,20], the heterogeneity of bioenergy pathways and their dependency on biomass and land resources adds several dimensions to the problem of policy design under uncertainty (see Table 1).

Firstly, the future costs of bioenergy provision depend not only on the extent of cost reductions associated with technological progress and learning by doing, but also on resource cost developments, which are in turn influenced by the demand for competing biomass uses; as a result, the future competitiveness of bioenergy pathways can be associated with large uncertainties [21]. Moreover, bioenergy production can give rise to external costs (e.g. through negative impacts on biodiversity, soils, water quality and availability), which depend on the pathway in question as well as on local and regional circumstances [22]. On the benefit side, not only the level and slope of the aggregate marginal benefit function of GHG mitigation is uncertain [23,24], but also the extent of emission reductions associated with different bioenergy pathways, because estimates of GHG balances require numerous assumptions [25–27]. The complexity of estimating GHG mitigation benefits grows, once indirect land use effects of an increased biomass demand are taken into account [28,29]. Also, it is difficult to assess benefits related to the security of electricity supply; those relating to the substitution of imports depend on which fuels are replaced by bioenergy, whereas the value of systemic benefits of flexible bioenergy provision depends on the future availability of low carbon alternatives, such as storage systems, and their competitiveness.

Finally, given the existence of multiple externalities, policy makers face the challenge of how to weigh external costs and external benefits of a given pathway against each other and solve associated trade-offs. Moreover, uncertainties do not only apply to bioelectricity pathways, but also to the use of biomass in transport, heating and material applications in the growing bioeconomy. The optimal future allocation of scarce biomass resources remains unknown, because the future availability of alternative, non-biomass GHG mitigation options in the different sectors determines where biomass use would generate the largest benefits.

In the implementation phase, a further dimension of uncertainty applies to the response of actors to policy incentives. An important influence factor on market actors' behaviour is the degree of policy uncertainty they perceive: the profitability of investments depends heavily on policy incentives, so that market actors will only be willing to carry them out if they have sufficient safeguards and confidence in their continued existence [20,30,31]. Policy makers therefore face a trade-off: over time, as the policy is implemented, new information becomes available and learning takes place, reducing some of the uncertainties named above. The flexibility to adjust the policy, however, results in an increase in policy uncertainty. On the other hand, policies which create very stable expectations and ensure high planning security reduce uncertainty about how market actors will respond to them, but flexibility to correct errors and respond to new developments is lost. In this paper, we explore what answers economic theory has to offer for dealing with this trade-off, and apply findings to the analysis of two case studies.

**Table 1 – Major uncertainties in bioenergy policy making.**

| Stage of political decision making | Type of uncertainty | Dimensions |
|---|---|---|
| Rationale for bioenergy support and design of support mechanism | Static cost uncertainty | Uncertainty about private costs of bioenergy production, i.e. the position and shape of the aggregated marginal cost curve of bioenergy producers is not known to policy makers |
| | Dynamic cost uncertainty | Uncertainty about cost reductions through learning curve effects and economies of scale<br>Uncertainty about resource cost developments |
| | Uncertainty about external costs of bioenergy production | Uncertainty about negative externalities associated with a specific bioenergy pathway (arising from e.g. negative impacts on soils, water quality and availability, biodiversity, particulate emissions during bioenergy conversion and use) |
| | Uncertainty about GHG mitigation benefits | Uncertainty about aggregate marginal damage function of GHG emissions<br>Uncertainty about GHG balances of bioenergy pathways<br>Uncertainty about indirect land use changes and associated GHG emissions |
| | Uncertainty about security of supply benefits | Uncertainty about benefits of import substitution<br>Uncertainty about future competitiveness of bioelectricity plants' contributions to system stability |
| | Uncertainty about how to balance multiple externalities | Uncertainty about what weight should be given to which external benefits and costs |
| | Uncertainty about optimal biomass allocation | Uncertainty about current and future conditions of reference systems in different energy and bioeconomy sectors |
| Implementation of support scheme | Uncertainty about the response of actors to policy incentives | Uncertainty about the correctness of behavioural assumptions (e.g. concerning rational behaviour)<br>Uncertainty regarding interactions between bioenergy policy incentives and other policies and macroeconomic framework conditions<br>On the side of market actors, uncertainty about the credible commitment of policy makers (policy uncertainty) |

In handling uncertainties in deployment support, three parameters of instrument design appear particularly relevant: the choice between price and quantity instruments, the differentiation of support between various bioenergy technologies and feedstocks, and the mechanism for implementing policy adjustments. Applying insights from the price vs. quantity literature, new institutional economics, and the theory of risk allocation, Section 2 discusses implications for the design of these parameters under simultaneous cost and benefit uncertainty. Also, it is examined which issues are regarded as solved in the literature, and which remain problematic. Focussing on the latter, Section 3 analyses two case studies of different solutions which have been adopted in practice: the UK Renewables Obligation as an example of a quantity-oriented instrument in which market actors' technology and feedstock choices have to comply with sustainability requirements; and the German feed-in tariff/feed-in premium scheme as a price-oriented instrument, in which policy makers decide on which pathways show acceptable cost-benefit-balances to merit reference cost-based support. The case studies have been chosen based on instrument characteristics, and because in both countries, bioenergy is envisioned to make a sizable contribution to RES targets, making bioenergy policy design a question of high interest (see Fig. 1). Both in the UK and Germany, deployment support schemes are currently in transition (to the Contracts for Difference (Cfd) scheme and a competitive bidding scheme, respectively). Insights about how existing schemes have performed in addressing uncertainty-related challenges can provide relevant lessons for this process – the more so, since questions regarding the design of technology differentiation and adjustment mechanisms are not specific to a particular instrument type. Following a discussion of policy recommendations, Section 4 concludes.

## 2. Handling uncertainty in instrument choice and design – contributions of economic theory

Bioenergy policy makers have to make decisions under uncertainty about the level and slope of both the aggregated marginal cost (MC) curve of bioenergy production, including private and external costs, and the aggregated marginal benefit (MB) function, including various external benefits (see Fig. 2). Some aspects of this problem have drawn considerable attention in economic research and robust solutions have been proposed. For example, the inability to identify an optimal degree of bioenergy provision due to uncertainty about the intersection of MC and MB curves has been addressed by the standard-price approach, which seeks to implement a politically set target at least costs to achieve "efficiency without optimality" [33]. Other aspects remain more problematic. In the following, economic theory implications are examined for the questions of choosing between price and quantity instruments, technology differentiation, and policy adjustment.

### 2.1. *Choice between price and quantity instruments under uncertainty*

Since Weitzman [35] it is well established that under uncertainty, price and quantity instruments are not equivalent in their effects. Particularly, the presence of cost uncertainty is

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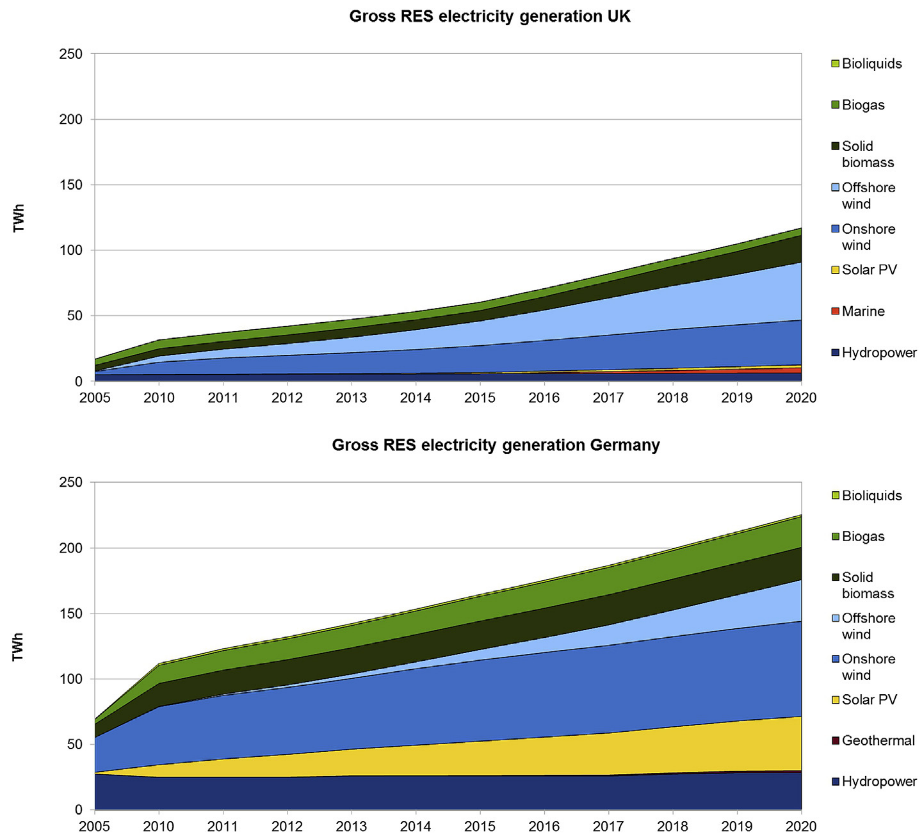


**Fig. 1 – Expected role of bioenergy in meeting the EU Renewable Energy Directive's 2020 targets in the electricity sector: projections for Germany and the UK according to National Renewable Energy Action Plans. Source: own illustration, based on data from ECN [32].**

found to affect the efficiency of instrument choices, whereas errors in assessing the MB curve's position result in the same social costs for both instrument types [33,36,37]. Under uncertainty about the MC function, quantity instruments such as

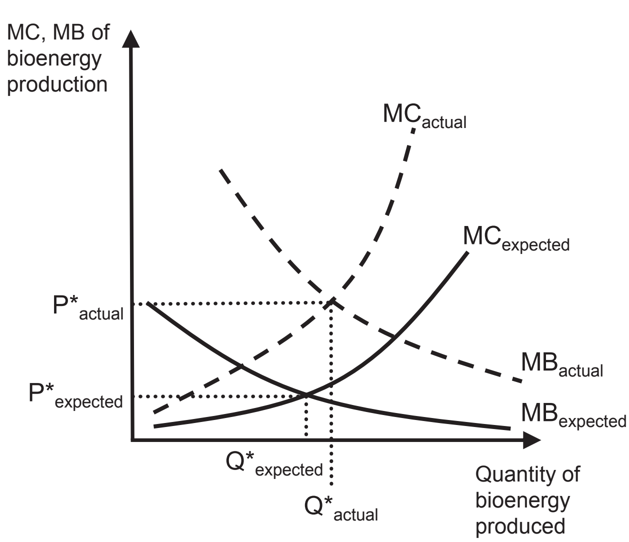


**Fig. 2 – Simultaneous uncertainty about the marginal cost and benefit curves of bioenergy production. Note: P*: optimal price; Q* optimal quantity; MC: marginal costs; MB: marginal benefits Source: based on Hepburn [34].**

renewables quotas or competitive bidding processes assure that a given target is reached, but the costs of doing so remain uncertain; market actors exploit the cheapest RES options first, but then move on to successively more expensive options. Price instruments, such as feed-in tariffs, offer a higher degree of cost control; the most expensive technology employed will be the one which is just about profitable under a given feed-in tariff rate. However, meetings targets will require repeated adjustments of price incentives, which can increase policy uncertainty for RES investors [19].

The advantages of adopting price or quantity instruments under uncertainty depend on the relative slopes of MC and MB curves [35]. If the MC curve is comparatively steep, price instruments will achieve a better welfare result; whereas if the MC curve's slope is comparatively gentle, a quantity instrument would be the favoured solution. In the case of $CO_2$ emissions, it is argued that the MB curve is relatively flat at least in the short-to mid-term [23,24]. As to the MC curve of RES, Menanteau, Finon and Lamy [19] and Finon and Perez [20] argue for a relatively flat curve on a large range of cumulative installed capacity; this would favour a quantity instrument, because a price instrument could lead to large errors in target achievement. In the case of bioenergy, however, the MC curve's slope depends on whether the scale of bioenergy expansion aimed for is significant compared to the available resources. The MC curve may be relatively flat for low levels of bioenergy use relying on the use of low competition feedstocks, but it is likely to grow steeper for higher levels of implementation, if competition for feedstock and land increases [21,38]. Therefore, the relative advantages of price and quantity instruments may change depending on the scale of bioenergy use.

Other relevant factors in the choice between price and quantity instruments are static and dynamic efficiency considerations. Quantity instruments perform better in exacting pressure to reduce costs, because producers compete on a price basis; price instruments allow producers a higher surplus by comparison [19]. Producers can take this surplus as profit, but also invest it in research and development activities, to bring down costs and increase future profits. In this case, associated knowledge and learning spillovers would speed up innovation. With a quantity instrument, on the other hand, risk adverse investors will require price premiums to compensate for price volatility, increasing the costs of achieving targets [19,20].

Nonetheless, some open questions remain, which appear relevant for bioenergy policy. In practice, policy makers often opt for hybrid instruments with both price and quantity elements [34]. In the case of bioenergy with its multiple market failures and uncertainties, it is of interest whether such combinations increase or decrease efficiency. Furthermore, Stavins [39] shows that benefit uncertainty does matter if it is correlated with cost uncertainty, and can in fact reverse price versus quantity recommendations in such cases. While a positive correlation favours quantity instruments, a negative correlation increases the advantages of price instruments. With bioenergy, it seems reasonable to assume a non-zero correlation, but depending on the pathway in question, it may be negative or positive. For example, the use of lignocellulosic feedstocks grown on marginal land can provide beneficial GHG balances and environmental cobenefits, but can also increase production costs [40]. The use of low competition wastes likewise allows for high GHG savings, but at low costs. Given that it is not feasible to estimate relative slopes and correlation effects for all bioenergy pathways and implement separate instruments, the problem of heterogeneous pathways needs to be addressed through selection mechanisms as part of technology differentiation.

### 2.2. *Differentiation between technologies and feedstocks*

Policy makers can set framework conditions and leave technology and feedstock choices up to market actors, or try to steer choices more directly by setting technology- and/or feedstock-specific incentives. Technology neutral support incentivises the use of RES technologies with the lowest costs; however, when respective potentials are exhausted, there is a sharp increase in marginal production costs, because the next cheapest technology is still at a market introduction stage [19,20]. Dynamic efficiency considerations therefore argue for a differentiation of support, to move a portfolio of RES technologies down the learning curve and reduce costs of RES production in the long term. In EU member states, RES support instruments show convergence towards the use of technology differentiation, irrespective of whether price or quantity instruments are used [41].

In the case of bioenergy, cost characteristics of pathways are very heterogeneous, depending on feedstocks and the technologies' stage in the learning curve. This poses the question what degree of differentiation would be sensible within the technology group of bioenergy. A uniform support level for all bioelectricity options without any further selection mechanism does not seem promising; this would incentivise the use of low-cost technology–feedstock combinations, but disregard differences in external costs and benefits. Basic options for differentiation would be:

1) A uniform support level with minimum sustainability criteria: here, all technology–feedstock combinations would be eligible for support, as long as they prove compliance with minimum criteria regarding external costs and benefits.
2) Technology-specific support levels: here, different technology–feedstock combinations receive different levels of support, according to policy makers' assessment of their specific cost and benefits.

In evaluating the respective advantages of alternatives, new institutional economics can offer useful insights. An important distinction is the degree of incentive intensity and planning security that alternative differentiation mechanisms imply [42,43]. Incentive intensity is high, if bioelectricity producers face high-powered market incentives to search for low-cost solutions. If, on the other hand, policy makers steer technology choices more centrally by offering high investment safeguards for selected technologies, incentive intensity to engage in decentralised search processes is lower, but bioelectricity producers have higher planning security for their investments. In case of a uniform support level with no further differentiation beyond sustainability requirements, technology choices are made by market actors, who can use dispersed and context-dependent information in developing solutions [43,44]. Independent of whether the support level is fixed centrally or determined competitively, bioenergy investors would have a high incentive intensity to reduce production costs and costs of compliance with sustainability criteria, in order to maximise profits. However, there would be few incentives to provide external benefits exceeding minimum requirements. In case of technology-specific support levels, greater information requirements apply to policy makers, which have to decide on which support level to grant to which technologies. As decisions apply to all eligible bioenergy projects, costs of errors are large; on the other hand, transaction costs are likely to be lower than under sustainability certification [45]. The more detailed prescriptions made by policy makers become, the lower is the incentive intensity for market actors to engage in search processes.

Different forms of technology differentiation have implications for type and level of uncertainties that market actors and policy makers face, as has the choice between quantity and price instruments (see Fig. 3). If remuneration is determined by markets (such as in quotas or bidding schemes), and producers have to prove compliance with sustainability criteria taking into account most recent scientific knowledge, a large share of cost- and benefit-related uncertainties is borne by market actors. If policy makers select specific bioenergy pathways for which cost-based support is provided,

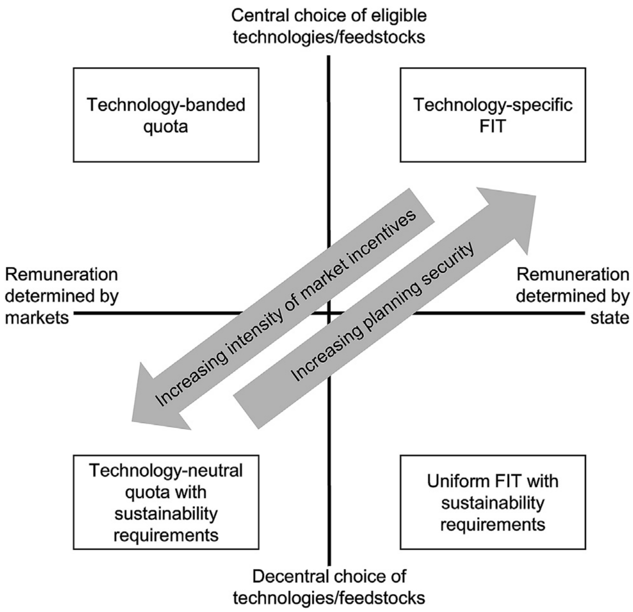


**Fig. 3 – Alternative options for differentiating between bioenergy technologies and feedstocks Note: FIT and quota schemes are used as illustrative examples.**

and credibly assure that support for existing plants will not be affected by changes in framework conditions or advances in scientific knowledge, the brunt of uncertainties is borne by the state. While this lowers incentives for reducing costs or improving environmental balances, planning security for investments is significantly higher. This is particularly important for transactions with a high degree of asset specificity, such as investments in dedicated biomass plants, whose profitability depends on the ongoing existence of policy incentives. Without sufficient investment safeguards, asset specific investments would require high price premiums to be realised, or not be undertaken at all [20,42].

In balancing incentive intensity and investment safeguards, it seems sensible to share uncertainties in the regulatory contract. As to who should bear which uncertainties, the theory of risk allocation offers some insights [46,47]:

1) Risk should be allocated to actors who can best control the risky outcome, i.e. actors who can influence the risky variable or can at least limit risk.
2) Risk should be allocated to actors who can bear it at the lowest costs; e.g. because they are less risk-averse, because they can hedge risks and insure against them, or because they can spread risks among many people.
3) Transaction costs (including information, negotiation, contract implementation and monitoring costs) of allocating risks among parties must be taken into account.

Originally applied to problems of policy design under risk, these insights can be transferred to problems involving more far-reaching uncertainties – under risk, the probability distribution of outcomes is known, whereas under uncertainty, this is not the case [48]. For the sake of simplification, uncertainty is here understood to encompass both forms of incomplete knowledge.

Who can bear uncertainties at the lowest costs is discussed controversially in the literature. For example, the state can spread out cost uncertainties among tax payers, but inefficient incentives in public administration can reduce the effectiveness with which they are managed [47,49]. The transaction costs of allocating uncertainties depend on their current allocation, and are therefore strongly context-dependent. Here, we focus on the degree of control over uncertain outcomes.

In general, the ability to use dispersed knowledge gives market actors an advantage in dealing with private cost uncertainties, particularly those that can be described as "normal market uncertainties" (e.g. uncertainties about price and resource cost developments). The state has clear advantages in deciding about the balancing of externalities. Moreover, while the optimal current and future allocation of biomass resources is unknown to market actors and policy makers alike, the latter can account for cross-sectoral interactions of policy and market incentives which influence allocative outcomes when designing policies. Less clear is the case with uncertainties relating to dynamic costs, external costs, GHG mitigation and security of supply benefits (see Table 2), making a more detailed analysis necessary.

### 2.3. *Policy adjustment*

Transaction cost economics-based policy analyses stress the importance of long-term commitment and credibility to enable an effective governance of transactions [20,50]. A certain incompleteness in regulatory contracts, which allows for flexibility, is part of ensuring this credibility, making adequate adjustment mechanisms a prerequisite for robust regulations [20,42]. Likewise, the theory of institutional change highlights the importance of being able to correct errors and to adapt to unforeseen circumstances [51]. In order to meet requirements of adaptive efficiency, adjustment mechanisms should ensure the potential reversibility of policy impacts, in order to avoid a lock-in into inefficient pathways of economic development. Moreover, policy measures should ensure openness to experimentation; the more actors' choices and innovation opportunities are constrained, the higher the risk of incurring a lock-in[51].

However, policy adjustments can lead to policy uncertainty, especially if they are discretionary in nature; for balancing flexibility and planning security, transparent provisions for renegotiation and adaptation and ex ante flexibility rules are recommended [50]. A related question is who should bear the costs of policy adjustments. Literature suggests that for adjustments associated with changes in political priorities, costs should be borne by the state, because otherwise policy uncertainty for investors would be too high [46]. For adjustments responding to new scientific knowledge, e.g. regarding GHG balances, it appears important that the planning security of plants already in operation is not compromised [34]. For example, research suggests that for bioelectricity supply chains based on forest residues, methane emissions during the storage of feedstocks may diminish GHG mitigation potentials [52,53]. Emissions can be reduced through technical drying, but this requires additional investments. Policy adjustments would need to find a compromise between

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**Table 2 – Allocation of uncertainties between market actors and the state – differences in the degree of control over uncertain outcomes.**

| Type of uncertainty | Ability to control outcome | |
|---|---|---|
| | Market actors | State |
| Static costs | (+) Control planning of investments and operation of bioenergy plants | (−) Can only indirectly influence investment decisions; information asymmetry between state and producers |
| Dynamic costs | (±) Control R&D investment decisions and sourcing decisions, but learning curve effects depend on aggregated market developments | (±) Can set incentives for innovation and diffusion of specific technologies |
| External costs of bioenergy production | (±) Production decisions affect external costs, but their extent may not be understood, and incentives are needed to take them into account | (±) State can promote improvements in scientific understanding, but environmental impacts can be strongly dependent on spatial context |
| GHG mitigation benefits | (±) Production decisions affect GHG balance, but impacts may not be understood, and incentives are needed to take them into account | (±) State can promote improvements in scientific understanding, and assess ILUC impacts; but actual GHG balance is determined by supply chain decisions |
| Security of supply benefits | (±) Production mode (flexible/inflexible) influences system benefits | (±) Benefits are determined by framework conditions (e.g. share of volatile RES, security of imports), but also depend on production and investment decisions |
| Uncertainty about how to balance multiple externalities | (−) Externalities affect wider public, not bioenergy producers | (+) Requires democratic decision making process |
| Uncertainty about optimal biomass allocation | (−) Allocative outcome results from aggregated demand and supply, as influenced by market and political framework conditions | (+) State influences allocation by setting policy incentives; cross-sectoral coordination of policy instruments required |

Note: (+) comparatively high degree of control over outcomes; (−) comparatively low degree of control; (±) control over some aspects of outcomes, not over others.

improving the GHG balance of existing plants and imposing additional costs on plant operators, so as not to inhibit future investments. In some situations, offering compensation for the costs of additional investments can be an option (see 3.3). Lastly, given that adjustments may affect the current and future allocation of property rights, political transaction costs of renegotiating regulatory contracts can be significant [54]; these too need to be taken into account when designing adjustment mechanisms.

Of course, adjustment mechanisms are not independent from other policy design choices. Therefore, an interesting question for bioenergy policy is whether it is possible to identify a higher compatibility of adaptive efficiency with price or quantity instruments and different approaches to technology differentiation, and what implications for policy uncertainty and transaction costs of adaptation arise. For these and the other open questions identified above, case studies can yield useful insights.

## 3. Case study analysis of the UK Renewables obligation and the German feed-in tariff/feed-in premium scheme

Exemplifying different approaches of instrument choice, technology differentiation and policy adjustment, this section analyses the UK Renewables Obligation (RO) [55,56] and the German feed-in tariff (FIT)/feed-in premium (FIP) scheme [57,58] to examine how theoretically interesting questions as identified under Section 2 have been addressed in practice. Regarding the choice between price, quantity and hybrid instruments, we first analyse how well the case studies succeed in minimizing social costs of errors. Then, we examine how uncertainties have been allocated in respective approaches to technology differentiation, and how trade-offs between incentive intensity and planning security have been solved. Lastly, we discuss adjustment mechanisms' implications for adaptive efficiency, transaction costs of adjustments, and policy uncertainty. Central characteristics of the RO and FIT/FIP schemes are summarised in Table 3.

### 3.1. *Prices versus quantities versus hybrids: the social costs of errors*

In quantity instruments, there is in principle a high uncertainty about what level of bioenergy use will be induced to fulfil RES quotas, and how high associated production costs and external costs will be. In the RO, this uncertainty is reduced by the price ceiling which places a limit on private costs at least; it limits uncertainty for obligated suppliers and signals the outer limit of feasible costs to bioenergy producers. For policy makers, the technology bands introduce a measure of control over the technology mix. On the other hand, the price ceiling increases uncertainty about reaching RES targets;

**Table 3 – Characterisation of the renewables obligation and the feed-in tariff/feed-in premium scheme as main support instruments in UK and German bioelectricity policy.**

| | | Characterisation of policy elements |
|---|---|---|
| UK | Legally binding targets | 34% GHG emission reductions by 2020, 80% by 2050 (base year 1990); 15% RES share in final energy consumption by 2020 |
| | Main support instrument | Renewables Obligation (RO) as quantity instrument with price ceiling (closes to new entrants in 2017, to be replaced by Contracts for Difference (CfD) scheme) |
| | Technology differentiation | Since 2009, technology bands determine the level of ROCs per megawatt-hour which RES receive for 20 years; bioenergy support levels depend on technology, feedstock, and time of a plant's accreditation under the RO |
| | Determination of remuneration | Value of renewable obligation certificates (ROCs) determined by markets (bilateral trading); buy-out price as price ceiling |
| | Incentives for GHG benefits | Minimum GHG reduction requirements, trajectory defined up to 2030 (for plants $\geq$ 1 MW) |
| | Incentives for security of supply benefits | 12 of 18 biomass bands apply to co-firing and conversions, to incentivise RES electricity production compatible with the existing electricity system |
| | Consideration of external costs | Compliance with land and forest sustainability criteria mandatory (for plants $\geq$ 1 MW) |
| | Adjustment mechanism | 4 yearly banding reviews, emergency reviews possible under specified circumstances (e.g. significant variations in net costs); ROC levels decline over time, while GHG reduction requirements increase |
| | Other RES support instruments in the electricity sector | Technology-specific feed-in tariffs for RES $\leq$5 MW (biomass: for AD only); CfD for large-scale RES and nuclear; EU Emissions Trading System with national carbon price floor in the electricity sector; R&D support |
| Germany | Legally binding targets | 40% GHG emission reductions by 2020 (base year 1990); 18% RES share in final energy consumption by 2020; 40–45% RES share in final electricity consumption by 2025, 80% by 2050 |
| | Main support instrument | Feed-in tariffs (FIT) as price instrument; sliding feed-in premium (FIP) as price instrument (to be gradually expanded to all RES plants > 100 kW until 2016); EEG 2014 has introduced a "breathing cap" as a quantity constraint on bioenergy expansion (100 MW per year). |
| | Technology differentiation | Cost-based, technology-specific FIT rates which producers receive for 20 years; these also act as FIP reference prices (FIP: compensates for differences between reference prices and average monthly market value of RES electricity). Bioenergy FIT rates depend on installed capacity, technology, feedstock, and time of commissioning; support is limited to dedicated biomass plants $\leq$20 MW electric capacity |
| | Determination of remuneration | Central, by policy makers; in FIP limited market element (direct marketing revenues may deviate from average market value used in premium calculation) |
| | Incentives for GHG benefits | Through choice of supported technologies and feedstocks; additional prerequisites for funding may apply (e.g. mandatory minimum heat use in EEG 2012) |
| | Incentives for security of supply benefits | Capacity-oriented flexibility premium; FIP offers possibility of increasing profits through demand-oriented feed-in and participation in balancing markets; additional requirements on biogas plant flexibility in EEG 2014 |
| | Consideration of external costs | Through choice of supported technologies and feedstocks; additional prerequisites for funding may apply (e.g. cap on maize and cereal grain use in EEG 2012) |
| | Adjustment mechanism | Revisions of the EEG when deemed necessary based on monitoring; between revisions, ordinances can be issued regarding specified topics; FIT rates decline over time |
| | Other RES support instruments in the electricity sector | EU Emissions Trading System; R&D support |

Note: only RO specifications for England and Wales are considered; different specifications apply for Northern Ireland and Scottish Renewables Obligations.
Sources: based on [55,57–61].

the same is true for the banded allocation of ROs, which distorts the direct link between the number of Renewables Obligation Certificates (ROCs) and the amount of RES electricity produced. For limiting uncertainty about external costs, sustainability certification constitutes the main instrument (see 3.2) [56].

In the FIT/FIP, policy makers have a more direct control of private costs; however, comparatively high levels of support have led to a large increase particularly in crop-based anaerobic digestion (AD), and a lively debate about associated external costs and total support costs [62,63]. The response were significant reductions in reference prices in 2012 and

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2014. Differences in technology and feedstock costs and energy yields [64] make it difficult to assess with confidence which bioelectricity pathways will respond how to changes in price incentives, adding to uncertainty about total future support costs as well as external costs. In response, the 2014 revision of the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG) has introduced an additional quantity constraint. If in the course of a year, the gross growth of installed bioenergy capacity exceeds 100 MW, remuneration rates are subject to an accelerated decrease (compared to the normal dynamic decrease). While limiting cost uncertainties for policy makers, this measure increases uncertainty for project developers.

Both price ceiling and quantity constraint introduce hybrid elements into RO and FIT/FIP, respectively, in order to limit the social costs of erroneous judgements about the MC curve of bioenergy production (see Figs. 4 and 5). In the RO, the price ceiling, which applies equally to all RES technologies, limits bioenergy expansion if it turned out to be more expensive than expected. If, conversely, bioenergy production was found to be comparatively cheap, ROC prices in the RO would adapt accordingly; the structure of RES production used to fulfil the quota would shift in favour of bioenergy. In the reference cost-based FIT/FIP, the quantity constraint guards against lower-than-expected production costs, which would lead to higher levels of bioenergy use than envisioned. The constraint's design as a “breathing cap” would allow bioenergy production to expand even once the accelerated decrease in remuneration kicks in, until reference prices equal actual marginal costs. However, if the MB curve of bioenergy use was steeper than expected, the quantity constraint could lead to errors on the side of caution if set too low. While the RO's price ceiling primarily limits private costs, the FIT/FIP's quantity constraint offers a certain degree of control over external costs as well, if these are likely to increase with the extent of bioenergy expansion. Therefore, “breathing caps”, which adjust remuneration depending on the amount of capacity already installed within a certain period, can be a sensible option for reducing uncertainty about the social costs of errors for policy makers. However, it remains challenging not to set the quantity constraint too high or too low, and also, an adequate planning horizon for adjustments is needed. In case of the EEG 2014, the constraint is likely to be set too low and the three-monthly adjustment period too short to allow for an effective steering of dynamic developments [65].

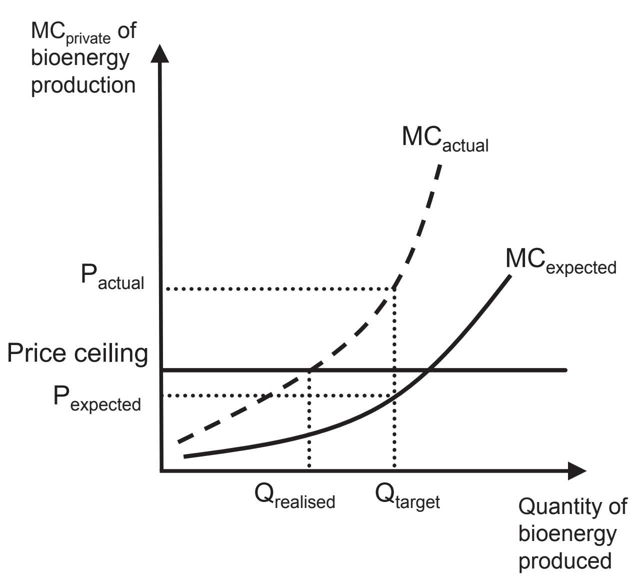


**Fig. 4 – Effects of the RO's price ceiling under cost uncertainty. Source: based on Menanteau, Finon and Lamy [19].**

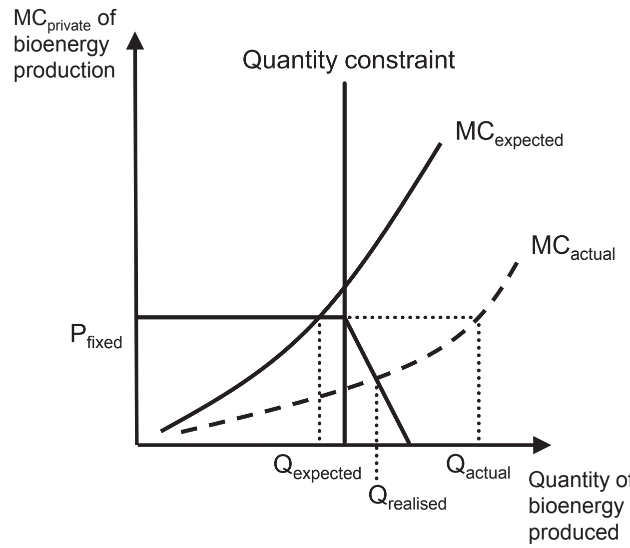


**Fig. 5 – Effects of the FIT/FIP scheme's “breathing cap” as a quantity constraint under cost uncertainty. Source: based on Menanteau, Finon and Lamy [19].**

### 3.2. *Technology differentiation: allocation of uncertainty, incentive intensity and planning security*

Both cases adopt a technology-specific approach, but the degree to which policy makers centrally steer technology and feedstock decisions differs. Under the RO, the cost-side of decisions is left to market actors, who need to assess what technologies and feedstocks are likely to be viable under ROC contracts. The steering influence of policy makers is limited to setting bands, with the relative number of ROCs for certain technologies and feedstocks depending on expectations about current costs and innovative potential. However, there is no direct control over whether technologies are actually taken up. On the benefit side, sustainability certification ensures compliance with minimum standards, reducing uncertainty about GHG mitigation benefits and external costs of bioenergy production for policy makers. At the same time, a larger share of these uncertainties is allocated to market actors, who have to ensure that their supply chains meet sustainability requirements. To dampen uncertainties for bioenergy producers, there is a progressive tightening of GHG requirements which allows for an improvement of supply chains over time, and a one year period in which only reporting is required. Also, GHG accounting methodology is provided by the state, as well as a guarantee that neither it nor the GHG trajectory will be changed unilaterally until 2027 [56]. As a result, the state takes on part of the scientific uncertainty, although the problem of undertaking a credible self-commitment in face of major new discoveries remains. Moreover, policy makers bear uncertainties related to external costs not reflected in sustainability criteria; in effect, bioenergy producers have few incentives to provide a higher level of environmental performance than required in the defined minimum requirements. For security of supply benefits, there is no special steering mechanism, but co-firing or the conversion of fossil fuel plants, where biomass directly replaces coal, is seen as compatible with envisioned electricity sector developments [66]. Compared to Germany, this reflects the UK's focus on a low carbon transition with ongoing central, non-intermittent power production and a strong role for nuclear power and CCS, instead of a more decentralised energy transition with large shares of intermittent RES.

By setting FIT/FIP reference prices and additional eligibility requirements, policy makers in Germany have a more direct control over what technology–feedstock combinations are likely to be profitable and realised. By setting fixed prices, policy makers take on a large share of static and dynamic cost uncertainties, although bioenergy investors have to handle uncertainty about feedstock cost developments which affect plant profitability. In the absence of minimum GHG mitigation requirements and certification, GHG uncertainty is also fully borne by policy makers, same as uncertainty about external costs. By providing feedstock-specific tariff rates, the EEG 2012 attempted to set incentives for the use of feedstocks with a beneficial environmental balance but comparatively high costs [67]. Moreover, minimum heat use requirements and a cap on maize in biogas plants were used to enhance GHG benefits and limit external costs. The EEG 2014 has abolished feedstock differentiation and additional requirements – the expectation is that only pathways based on wastes and residues will remain profitable under strongly reduced general remuneration, which would by default have good GHG balances and low external costs [68]. However, it is uncertain whether this will be so, given that many low-cost wastes and residual potentials are already in use [65]. Concerning security of supply benefits, positive incentives for flexible production are provided in both EEG 2012 and 2014 (see Table 3). Additionally, the current revision introduces certain requirements for new biogas plants, which aim at making flexible production the only viable model. The use of inflexible requirements, however, poses the risk that benefits of other concepts (e.g. biogas CHP) may be neglected.

In sum, in the FIT/FIP scheme policy makers bear a significantly larger share of uncertainties about static and dynamic costs, GHG benefits and external costs than under the RO. While this allows for a higher degree of control over developments in the bioelectricity market, information requirements on policy makers are high, leading to frequent adjustments of reference prices and eligibility requirements [67]. Meanwhile, differences in the allocation of uncertainties have important implications for incentive intensity and planning security. In Germany, there is a high degree of planning security for plants once they become operational, as changes in reference prices and requirements only affect new plants; therefore, the FIP/FIT scheme has been successful in attracting high levels of asset specific investments [69]. While incentives to reduce costs result from profit maximisation, savings in the operation of existing plants are not passed on to society; however, new plants can benefit from accelerated learning curve effects. As for GHG benefits and external costs, incentive intensity to implement improvements is low for existing plants. New plants have incentives to improve environmental balances insofar as a tightening of requirements is expected in upcoming revisions (see 3.3).

In contrast, the RO, where market actors bear a larger share of cost and benefit uncertainties, provides strong incentives to lower production costs, as long as minimum sustainability criteria are complied with. Also, the progressive tightening of GHG requirements sets incentives to improve GHG balances over time. Investors have planning security regarding the level of ROCs they receive and the nature of sustainability criteria, as long as the commitment not to undertake unilateral changes is considered as credible. However, particularly asset specific dedicated biomass projects have to be very confident they can secure adequate contracts for their ROCs and meet sustainability criteria to be viable in the long run. As a result, bioenergy expansion in the UK focuses on co-firing as a reversible option with a high adaptability to changes in market conditions, while investments in asset specific technologies such as AD remain at much lower levels than in Germany [70].

### 3.3. *Adjustment of support schemes: transaction costs of adaptation, adaptive efficiency, and policy uncertainty*

In Germany, adjustments to new information regarding private and external costs, or GHG and security of supply benefits, require a revision of the EEG, in which major changes may be implemented. Given the high stakes involved for bioenergy and other RES investors, political transaction costs of revision processes can be significant. At the same time, reversibility of past policy decisions is low, because bioenergy technologies receive remuneration according to the version of the EEG they became operational under for 20 years. Changes applying to existing plants would counteract the protection of existing investments, with lasting impacts on political credibility and planning security. An exception are ordinances authorised as part of the EEG, which allow for a simplified legislative procedure to pass regulation on specific topics, which may then also pertain to existing plants. For example, the EEG 2012 and EEG 2014 authorise an ordinance on the introduction of sustainability criteria for solid and gaseous bioenergy carriers. However, it is not clear yet when requirements will come into effect and what exactly they would entail; this also depends on developments in EU legislation. For incentivising demand-oriented production behaviour, the EEG 2012 introduced the sliding FIP in combination with a flexibility premium for biogas plants which compensates for the costs of investments in plant flexibilisation [67]. The measure is associated with additional support costs, but increases existing plants' ability to generate security of supply benefits without compromising their planning security. Meanwhile, by steering technology choices through detailed specifications and eligibility requirements, openness to experimentation is restrained; however, the degree to which detailed specifications apply varies between technologies and versions of the EEG.

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In the UK, banding reviews are used to incorporate new information. In these, stakes for investors are also quite high; however, given that only ROC levels are determined, not remuneration rates as such, information requirements for policy makers and political transaction costs may be somewhat lower compared to the FIT/FIP scheme. The market-based determination of remuneration also improves the reversibility of policy decisions – even though ROC levels per megawatt-hour are guaranteed for 20 years, their value is not constant; if production costs, for example, were lower than expected, the quantity of bioenergy ROCs would increase, leading to an eventual decrease in ROC prices and profitability of new investments. In this way, a degree of automatic feedback is established. New information about GHG balances or external costs, meanwhile, would require an adjustment of sustainability criteria; here, the commitment not to change at least GHG mitigation requirements until 2027 limits the reversibility of policy decisions. While having security about the GHG reduction trajectory is important as an investment safeguard, the remaining degree of flexibility depends on how undertaking "non-unilateral" changes involving producers and other stakeholders will be implemented in practice; while this might entail a high transaction cost process, it could also potentially become an example of inclusive decision-making, which Upham, Riesch, Tomei and Thornley [71] recommend for dealing with bioenergy-related uncertainties. Given that market actors are free to decide the parameters of their projects, as long as as they fall into technology bands and fulfil sustainability criteria, the RO's openness to experimentation seems reasonably high.

Overall, the adaptive efficiency of the German FIT/FIP scheme appears to be rather low; conversely, policy uncertainty for existing plants is also low. Nonetheless, the need for frequent revisions to incoporate learning imposes policy uncertainty on future bioenergy investors and technology developers. In the RO, technology choices are more decentralised by comparison, resulting in higher adaptive efficiency. Particularly the use of sustainability certification which sets clear framework conditions and leaves detailed technology and resource decisions to producers may perform better than a central steering of choices; however, it is of central importance how the process for implementing changes to criteria and methodology is designed. Accordingly, policy uncertainty for existing plants in the RO mainly results from potential changes in sustainability requirements, while for future investors and technology developers, the future development of other political framework conditions such as the stringency of RES targets and deployment support levels are also relevant.

### 3.4. *Implications for bioelectricity policy design*

Table 4 summarises main findings of the case study analysis. The results show that there is no easy answer as to which instrument type and design options perform best overall – rather, both schemes reflect different choices regarding the balancing of trade-offs. Accordingly, policy recommendations have to take different priorities of policy makers into account, as well as the country-specific context.

For differentiating bioenergy pathways according to GHG benefits and other environmental impacts, for instance, sustainability certification shows several advantages over a central steering of technology and feedstock choices. It performs better in encouraging decentralised search processes, and incentivises improvements over time, if requirements are tightened. Moreover, it promises advantages in terms of adaptive efficiency (see Table 4), although this requires a careful design of adjustment processes that leave room for policy learning while enabling market actors to form stable expectations. However, the implementation of sustainability certification is associated with significant transaction costs [45]. In the German case with its focus on small to medium-scale plants, bioenergy value chains are predominantly regional, reducing uncertainty about legal framework conditions of biomass production compared to the UK, where imports of solid biomass play an important role [59,69,70,72]. Also, smaller average capacities result in a higher number of actors who have to engage in certification activities, increasing transaction costs. In such a context, a central steering approach to technology differentiation can be the more efficient option. Here, it would be advisable to use eligibility criteria to guide plant design and operation decisions with central impacts on GHG balances and other environmental effects, as adopted in the EEG 2012. Otherwise, uncertainty about the net external benefits of bioelectricity production would be high. To reduce policy uncertainty about future adjustments, it would be recommendable to credibly commit to strategic guidelines for future bioenergy policy, including for example a prioritisation of GHG mitigation as a policy aim [73,74].

The choice between price and quantity instruments likewise reflects political priorities. The RO sets high-powered incentives to search for low cost options within technology bands, but accepts low planning security for market actors. The prioritisation of static cost-effectiveness concerns is reinforced by the ROC price ceiling, which limits the private costs of RES expansion but increases uncertainty for producers. This is reflected in the preference for bioelectricity options with low asset specificity such as co-firing and conversions, which can be redeployed if political and market framework conditions change. More generally, the focus on static cost-effectiveness has resulted in a slower pace of RES expansion compared to Germany [75–77]. Political decisions to offer greater investment safeguards to RES producers have contributed to the introduction of feed-in tariffs for selected technologies in 2010 and the phase-out of the RO in favour of the CfD scheme [78]. The latter is designed as an administered sliding FIP, with a competitive bidding element when available budgets are breached [79]. In the German case, on the other hand, the price-based FIT/FIP scheme has been successful in incentivising high levels of asset specific investments, but the costs of implementing RES targets have proven to be a contentious issue in the political debate [63,80]. This has contributed to the recent strong reductions in reference prices for comparatively costly bioelectricity pathways; given the limited availability of low cost resources, this is expected to effectively put a stop on further bioelectricity expansion [65,72]. Remuneration cuts also limit the effectiveness of the newly introduced quantity constraint. In principle, however, the analysis shows that a well-designed "breathing cap" can be an effective solution for balancing

**Table 4 – Summary of case study results.**

| | UK renewables obligation | German FIT/FIP scheme |
|---|---|---|
| Minimisation of social costs of errors | • Banded ROC allocation supports diffusion of portfolio of RES technologies<br>• Price ceiling for ROCs limits private costs of bioenergy expansion, if they are higher than expected by policy makers<br>• Both measures increase uncertainty about meeting a target share of RES in electricity supply<br>• No direct control of bioenergy expansion levels | • Cost-based reference prices allow for direct control of technology mix<br>• Quantity constraint limits bioenergy expansion and total support costs, if private costs of bioenergy production are lower than expected by policy makers<br>• Coordination of technology-specific expansion corridors and overall RES targets remains challenging<br>• Frequent adjustments of support levels can increase policy uncertainty |
| Allocation of uncertainties | • Market actors bear uncertainties about ROC price developments, technology and feedstock costs<br>• Uncertainties about GHG benefits and external costs are shared by market actors and policy makers<br>• No specific steering mechanism for security of supply benefits | • Policy makers bear large share of static and dynamic cost uncertainties (except those concerning feedstock cost developments)<br>• GHG benefit and external cost uncertainties are borne by policy makers<br>• Specific incentives for provision of security of supply benefits |
| Balance between incentive intensity and planning security | • Strong incentives to lower production costs and costs of meeting sustainability criteria<br>• Dynamic incentives for improvements in GHG balance; apart from that, few incentives to improve environmental performance beyond minimum standards<br>• Planning security for existing plants is low, due to uncertainty about future remuneration levels and compliance of supply chains with sustainability criteria<br>• Result: preference for investments with low asset specificity (co-firing) | • Low incentive intensity to reduce production costs, as long as profits are satisfactory<br>• Few incentives to improve GHG balance and environmental performance, as long as eligibility requirements are met<br>• High planning security for existing plants<br>• Result: has incentivised high levels of asset specific investments (dedicated biomass plants) |
| Transaction costs of adjustment, adaptive efficiency and policy uncertainty | • Major adjustments require banding reviews; political transaction costs are somewhat lower than for the FIT/FIP scheme, due to lower information requirements<br>• Policy decisions are reversible to a certain degree, primarily through "non-unilateral" changes to sustainability requirements<br>• High openness to experimentation<br>• Long-term commitment to sustainability requirements reduces policy uncertainty, if considered credible; new projects face policy uncertainty about stringency of RES targets and ROC levels | • Major adjustments require revision of the EEG, with high political transaction costs<br>• Low reversibility of policy decisions<br>• Central steering of technology choices limits openness to experimentation<br>• Policy uncertainty is low for existing plants, but can be high for future investors and technology developers because of frequent adjustments of reference prices and eligibility requirements |

planning security for investors with control over overall support costs and expansion levels. RES deployment support in Germany, meanwhile, will transition to a competitive bidding scheme in 2017, reflecting a growing emphasis on increasing incentive intensity for cost reductions [81].

Given the new EU state aid guidelines' preference for competitive bidding schemes, implications for handling simultaneous cost and benefit uncertainties are a highly relevant topic for future research [82,83]. In principle, bidding processes could allow projects to compete on a cost as well as benefit basis, thereby providing a higher flexibility regarding feasible plant concepts. Once successful, investors would then have planning security that a certain remuneration would be received for a time span or contingent of megawatt-hours produced. However, past experiences with bidding processes reveal challenges relating to low implementation rates, high transaction costs and adverse impacts on market structure [84,85]. Moreover, if a bidding scheme was implemented on top of an existing FIT or FIP scheme, planning security for plants already in operation could be compromised, because new plants would enter into competition with old plants for low cost feedstocks. This illustrates the challenges of

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transitioning from a system of centrally steered technology and feedstock choices to a competitive system.

## 4. Conclusions

Using the UK Renewables Obligation and the German feed-in tariff/feed-in premium scheme as case studies, this paper has analysed the implications of alternative instrument choices and design options for the handling of uncertainties in bioelectricity deployment support. Our results show that for devising effective policies, not only choices between price and quantity instruments and central and decentral approaches to technology differentiation are relevant – in fact, different political priorities can make different solutions advantageous. In line with other institutionally-oriented analyses of RES policies [20,86–88], findings emphasise the importance of detailed policy design, which determines the exact balance between cost control, incentive intensity, planning security and adaptive efficiency. This includes the design of hybrid elements, such as price ceilings and quantity constraints, as well as policy adjustment processes. Here, consistency in policy decisions and the effective inclusion of stakeholders emerge as important guiding principles for policy design [30,71,87]. Finally, it needs to be stressed that the challenges of handling cost and benefit uncertainties of bioenergy use cannot be solved by deployment support alone – rather, it needs to be integrated into a wider policy mix, encompassing measures which support a functional innovation system for low carbon technologies as well as effective framework conditions for sustainable land use.

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