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Contracting for the Second Best in Dysfunctional Electricity Markets[*]

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Abstract

Power pools constitute a set of sometimes complex institutional arrangements for efficiency-enhancing coordination among power systems. In many developing countries, where such institutional arrangements can't be established over the short term, there still can be scope for voluntary electricity-sharing agreements among power systems. Using a particular type of efficient risk-sharing model with no commitment we demonstrate that second-best coordination improvements can be achieved with low to moderate risks of participants leaving the agreement. In the absence of an impartial market operator who can observe production fluctuations in connected power systems, establishing quasi-markets for trading excess electricity helps to achieve some cooperation in mutually beneficial electricity sharing.

JEL: C73, L94, O13
Keywords: Electricity Trade, Risk Sharing Arrangements, Self-Enforcing Contracts

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1 Introduction

A well known problem of many developing countries is the deficient electric power infrastructure, characterized by low access to electric grid, unreliable power supply, inefficient generating capacities, poor maintenance, and losses in transmission and distribution (Eberhard et al. 2008, Foster and Steinbuks 2009, Sen and Jamasb 2012). Integration of electricity markets is frequently seen as a low-hanging fruit of improving the performance of these deficient systems, especially in a large number of developing countries, where standard textbook recipes of deregulation, privatization, and gradual creation of fully functioning wholesale and retail electricity markets are difficult, if not impossible, to implement in near decades (Besant-Jones 2006, Gratwick and Eberhard 2008, Joskow 2008, Kessides 2012). The potential economic benefits from connecting power systems are widely documented (Gately 1974, Gnansounou and Dong 2004, Pierce et al. 2007) and, among others, include the benefits of diversifying generation mix, achieving economies of scale, promoting competition, and reducing the need for new generation capacity. The latter reason for integration is especially compelling. Electricity is a largely non-storable commodity, with uncertain demand and supply. In particular, demand for electricity varies greatly with factors such as the weather, time of day, and season, while electricity supply can be subject to unexpected failure of generation units and unanticipated changes in the output of intermittent renewable generation such as wind. Consequently, to balance demand and supply of electricity in real time, it is necessary to maintain a large safety margin of flexible generation capacity that remains idle in the vast majority of periods. This capacity is associated with a large economic cost, given by the fixed costs of generation capacity. Connecting different power systems can reduce the need for such idle capacity, and hence realize the economic benefits of trade in electricity, especially in countries with a non-trivial share of intermittent electricity generation capacity.[1]

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[1] A number of recent studies conducted numerical cost-benefit analysis of interconnecting electricity systems, and all have found sizable economic benefits from cross-country electricity trade. For instance, Antweiler (2016) finds strong economic rationale for potential integration of North America's fragmented interconnections into a continental 'supergrid'. Trade gains from reciprocal load smoothing account for reduction of 4.5TWh/month of idle capacity for Canada and 22.8 TWh/month for the United States. These capacity gains are roughly equivalent to the size to about seven modern nuclear reactors or a dozen large hydroelectric dams in Canada, and 28 nuclear reactors or 65 Hoover dams in the United States. Abrell and Rausch (2016) employ numerical general equilibrium model to study the effects of electricity trans-

Recognizing these potential benefits a number of developing country regions, including Western and Southern Africa, Latin America, and most recently, South Asia, moved in the direction of integrating their electricity systems (Ochoa et al. 2013). Nonetheless, the empirical evidence indicates that, unlike in developed countries, regional integration of electricity markets in developing country regions, e.g., in West Africa, Central America, and South Asia, had a limited success. Despite significant potential benefits traded quantities remain extremely small even over existing cross-border transmission links. For instance, the interconnection capacity utilization of the West African Power Pool (WAPP) and the Central American Power Market (MER) was, respectively, 9% and 4% in 2012. Similarly, the share of cross-border trade to consumption in WAPP and MER power pools accounted for mere 5% and 2% (Oseni and Pollitt 2016). A functioning regional power pool in the South Asia is yet to be established despite vast potential gains from cross-border electricity trade in this region (Singh et al. 2015, Timilsina et al. 2015). There are a number of reasons for poor performance of electricity trading arrangements in developing countries, which include (1) high investment and financing costs of developed grid interconnections; (2) insufficient generating capacity to meet demand of the pool; (3) absence of functioning legal framework for cross-border electricity exchanges; (4) poor trust and mutual confidence among pool members; and (5) lack of regional regulation and mechanism for dispute resolution (Eberhard et al. 2008, Pineau 2008, Reinstein et al. 2011, Singh et al. 2015, Oseni and Pollitt 2016).

This study is concerned with the latter three reasons, all of which relate to weak institutional arrangements that are not capable of enforcing "contracts" among member states.[2] In developed countries electricity trading is facilitated and enforced through complex institutional mechanisms. These arrangements frequently feature an independent system

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mission infrastructure expansion for gains from trade and carbon dioxide emissions reduction in the European power sector. They find that large scale transmission infrastructure enhancements could deliver gains between 5.8 and 8.7 billion 2011$ per year, corresponding to an 0.06–0.09% increase in annual European welfare. Timilsina et al. (2015) use an electricity planning model to quantify the long-term benefits of unrestricted cross-border electricity trade in the South Asia. They find that the unrestricted electricity trade provision would save US$226 billion (US$9 billion per year) of electricity supply costs over the period of 2015–40.

[2] Interestingly enough, the opposite case of excess rigidity in renegotiating contracts was found to be a bottleneck in establishing independent transmission system operator and achieving greater regional integration of electric system in Netherlands (Mulder and Schestalova 2006). After these issues were resolved, a highly successful Norway–Netherlands interconnector was established.

operator or independent transmission system operator, which has responsibility for controlling the access to and use of the transmission grid by competing generators and retailers (Pollitt 2012). Electricity trading could take place in day ahead, hour ahead, and real time energy markets. Other institutions aimed at correcting different market and coordination failures include separate markets for locational marginal pricing, ancillary services, and financial transmission rights (Sioshansi 2008). On the contrary, in developing countries, where establishing effective cross-border institutions conductive to efficient electricity trade is a difficult task[3] (Maurer and Barroso 2011, Kessides 2012, Nepal and Jamasb 2015), electricity trading is dominated by bilateral contracts. Even in the Southern African Power Pool, the most advanced electricity sharing institution in developing countries, bilateral contracts account for more than 90 percent of electricity trade (Musaba 2009). In the absence of functioning legal framework and institutional enforcement mechanisms for cross-border electricity exchanges[4], these bilateral electricity trading contracts are subjected to a 'limited commitment' problem (Thomas and Worrall 1988, Kocherlakota 1996, Ligon et al. 2002), where countries may sign, or implicitly agree to, contingent electricity trading contracts but may also renege on these contracts when it is to their advantage. As we demonstrate in this paper, given the lack of mutual confidence between trading parties, the limited commitment results in lower and suboptimal volumes of electricity trade. Furthermore, if this problem is serious enough, the mutually beneficial electricity trade may not happen at all.

Given confidentiality provisions governing cross-border electricity trade in developing countries, the evidence of actual reneging on bilateral trading contracts is very difficult, if not impossible, to establish.[5] However, the energy policy literature has identified a number of electricity supply risk factors for international partners. One important risk factor is

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[3] This point is particularly relevant for cross-border electricity auctions, where the success of handful experiences has been mixed at best (Maurer and Barroso 2011, p. 73).

[4] Oseni and Pollitt (2016) note that there is a need for specific trade agreements and enforcement mechanisms to support electricity trade as World Trade Organization rules and arbitration bodies do not adequately address trade in electricity.

[5] These confidentiality provisions frequently extend beyond formal legal operating agreements, which again reflects weaknesses in cross-border enforcement mechanisms in developing countries. For example, Sebitosi and Okou (2010) cites proceedings of a workshop on Southern African PowerPool (SAPP) hosted by Purdue University. Workshop participants warned about a confidentiality requirement that some utilities had imposed on their generator cost data. This was despite the provisions about disclosure of information that were stipulated in the SAPP Operating Agreement.

the presence of frequent internal conflicts among the ruling elites, which make it difficult to reach consensus on many economic policies, including cross-border electricity trade.[6] In some electricity trading regions there have also been actual cross-border conflicts in the past (Southern African PowerPool, SAPP) or present (South Asia). These historical animosities create general lack of trust for implementing cross-border electricity trade (Schiff and Winters 2002). As noted by the CEO of the National Electricity Regulator of South Africa (Mkhwanazi 2003, p. 11):

> "... the unsatisfactory political climate in many parts of Africa is a serious constraint to greater co-operation in the power sector. It is difficult for normal commercial trading to take place in war zones. There is also often the lack of political will to undertake cross border ventures, and the lack of continuity of economic policies in some of the countries interferes with long-term planning. This lack of trust between some countries is a serious impediment to progress. It is also the case that many countries in Africa are already short of commercial energy themselves, and exporting electricity is obviously not a priority in such circumstances."

In presence of ongoing political tensions electricity trade is perceived as a threat to national interests and energy security issues are reflected in e.g., very slow progress over power trade between India and its neighbours (Mukherji and Chaturvedi 2013, Ravinder et al. 2016). Another risk factor relates to political economy issues, where politicians (and state-controlled utilities) have incentives to forego electricity export in favor of securing reliable power supply for domestic agricultural or industrial projects. For example, it is documented that in South Asia during election season state- or municipal-run utilities may have strong incentives to allocate their excess capacities for the needs of local agricultural consumers (who are highly organized, active, and carry significant weight in state elections) instead of selling them across the border (see e.g., Joseph 2010, Sen and Jamasb 2012). Another example is a recent collapse of the planned development of a 5,000 MW hydropower project by Western Power Corridor (Westcor), a venture comprising five African countries. Mbirimi (2010, p. 16) argues that "among the reasons given for

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[6] For an overview of internal conflicts among ethnic lines, and their detrimental effects on infrastructure in Subsaharan Africa, see Easterly and Levine (1997).

the collapse is political ‘indecisiveness’ on the part of the government of the Democratic Republic of Congo (DRC). However, it has also been alleged that the DRC government is more interested in a private power development project currently under construction in the country’s western Bas Congo Province, but which is primarily aimed at supplying power to an aluminium smelter being developed by BHP Billiton.”

The outlined reasons for limited commitment are aptly summarized by Woolfrey (2016):

> “While the development of regional interconnectors is a necessary requirement for electric power trading, it is not sufficient, and in order for a power pool to successfully bring about its intended benefits, it requires political buy-in from its participants. [...] Trading electricity adds an international political dimension, introducing issues such as national energy security and sovereignty over regulation. A crucial issue for power pools is whether electric power trade is deemed politically acceptable, especially in importing countries. For potential importers, the main concern is security of supply. They need to have confidence that exporting countries within a regional power trade arrangement will continue to supply electric power in a predictable and reliable way, or not use it as a political or diplomatic pressure tool. Importing countries also have to accept that, at least in some cases, importing power generated elsewhere means foregoing potential construction jobs at home.”

Thus, for electricity exchange between developing countries to take place, any contractual relationship between utilities located in different countries should be self-enforcing. That is, at each moment in time, it should be in the interest of each electric power provider to participate in an electricity sharing arrangement. Every time a participating provider is called upon to transfer electricity to a neighboring country, it weighs the cost of fulfilling this obligation against the benefit from future cooperation. The electricity sharing arrangement is self-enforcing as long as the discounted present value of the future benefit flow outweighs the current cost. The possibility that a power system may abandon the electricity sharing arrangement at any moment of time limits the scope for cooperation. In particular, electricity sharing arrangements that exploit unpredictable fluctuations in supply/demand tightness conditions are difficult to implement.

The aim of this paper is to study the scope for voluntary electricity sharing arrangements among power systems where functioning institutional arrangements for more formal cooperation do not exist. We start with a premise that an interconnector can be a substitute for reserve generation capacity in the connected power systems, provided that stochastic variations in demand and supply are not perfectly positively correlated across these systems. A power system that is subject to a negative supply shock (e.g. drought or low wind) can import power from a neighboring system that is not subject to the same shock. Thus connecting power systems could bring welfare gains through reduction in volatility of demand/supply imbalances even without a consistent difference in the timing of peak demand periods.

As a base framework, we adapt the efficient risk sharing model without commitment to electricity sharing arrangements. The model has been developed theoretically, among others, by Thomas et. al, (1988, 2014), Kocherlakota (1996), and Kletzer and Wright (2000), and subsequently applied to understanding informal contracts in developing countries (Foster and Rosenzweig 2001, Albarran and Attanasio 2003, Ligon et al. 2002, Schechter 2007, Dubois et al. 2008). To our knowledge this is the first time this framework is applied to study electricity markets.

We assume that two developing-country power systems invest in an electricity interconnector and choose its transmission capacity endogenously. Once connected, the power systems use the installed capacity to barter electricity without using money. The lack of monetary transfers is restrictive insofar as it requires the electricity sharing arrangement to run a 'balanced budget' over the relevant time horizon (which *inter alia* depends on the degree of mutual trust between the power systems). By relaxing the 'balanced budget' requirement, cross-border electricity trade at scarcity prices could potentially achieve better outcomes, but it would also create a financial burden to local governments or exacerbate financial fragility of power utilities.[7]

As many developing countries experience power shortages, with their energy demand needs vastly outstripping supply, we assume that each power system operates close to its full generation capacity and the electricity supply is perfectly inelastic. Furthermore, elec-

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[7] Our proposed solution does not disregard scarcity prices, as the electricity exchange is governed by the appropriate shadow prices.

tricity supply is subject to random production shocks, which reflect unexpected failures of generation units or unanticipated changes in the output of intermittent renewable generation. By entering a cooperative arrangement, each power system promises to transfer some of the electricity it produces to the other power system, whenever such transfer is required. To capture the need for the electricity contracts to be self-enforcing, the model features forward-looking intertemporal participation constraints. Thereby at any moment of time and for any realization of electricity production shocks, the discounted expected utility from participating in an electricity sharing arrangement is greater than or equal to the autarky payoff. Consistent with game-theoretic literature the implicit assumption in the formulation of the participation constraint is that a deviation from an electricity sharing arrangement triggers the most severe punishment, i.e, permanent termination of the arrangement.[8]

The model's main insight is that the scope for cooperation, i.e., the amount of electricity traded and the size of transmission capacity crucially, depends on predetermined risks of terminating an ongoing relationship due to, e.g., political economy issues in one or both countries that host the interconnector. As we have discussed above these risks are not trivial in many developing countries. If risks of terminating contractual agreements are small, the intertemporal participation constraints are never binding, and the first-best efficient contracting is self-enforcing. As the likelihood of terminating the ongoing relationship increases, the intertemporal participation constraints are binding infinitely often, and the first-best contract is no longer feasible. Nonetheless cooperation yields an improvement over autarkic outcome as it allows for some intertemporal smoothing of electricity consumption, and the investment in transmission capacity is desirable. If the expected probability of terminating an ongoing relationship is high (e.g., in cases of very substantial political risks), paying for the interconnector is no more optimal and the autarky is the only self-enforcing outcome.

We start with the assumption that implementation of the voluntary electricity sharing arrangements is facilitated by an independent system operator, which can perfectly observe production shocks in the connected power systems and on the basis of this information, recommend (in a non-binding manner) the appropriate dispatch. In this setting, the opti-

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[8] This assumption is made for computational convenience, but results would be qualitatively the same with less severe, but more realistic punishments (see footnote 20 for details).

mal electricity sharing arrangement entices a power provider with the binding intertemporal participation constraint to stay in the arrangement by promising an increase in its current and the future expected electricity consumption. The promised increase is just sufficient to prevent the exit of the constrained power system and the new higher expected consumption level remains unchanged as long as there are no other binding participation constraints.

In practice, even in developed countries, establishing an independent system operator is associated with significant costs (Federal Energy Regulatory Commission 2004), and these costs are likely to be even higher in developing countries. We show that if production shocks in the connected power systems are not perfectly observable by all parties, some welfare gains can still be realized through an electricity sharing arrangement, but these gains are lower relative to the previous case of fully observable electricity production. This happens because, to increase domestic electricity consumption, each power system is tempted to understate its current supply conditions. As shown more generally by Hertel (2004), to create sufficient incentives for truthful revelation of the production shocks, demanding an electricity transfer from the other party in the current period should be punished by lower expected future electricity imports, or, equivalently, exporting electricity in the current period should be rewarded by higher expected electricity imports in the future.[9]

We argue that with imperfect monitoring of production shocks, the feasible cooperative arrangements can be implemented via a quasi-market for trading excess electricity. For a quasi-market to operate, the connected power systems need to introduce notional coins (e.g., megawatt chips), which are worthless outside their cooperative arrangement. These chips can be used to keep track of electricity import/export imbalance between the parties to the contract; the party that runs out of chips needs to earn some back through electricity exports before it can receive further imports.

Some form of cooperative arrangements either through establishing an independent system operator or through quasi-markets enable realizing gains from electricity trade when institutional characteristics of developing countries make establishing more complex mar-

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[9] Atkeson and Lucas (1992) and Thomas and Worrall (1990) also study dynamic contracts in settings with private information. However, these papers assume full commitment, i.e., players are committed to the contract signed at the beginning and cannot walk away from it at the later date.

ket arrangements difficult. Of course, our results should not be interpreted as a substitute for the standard reform model. While in principle, restructuring and deregulation of electricity markets are not pre-requisites for successful international power sector cooperation, in many power systems, the processes of deregulation and integration went hand in hand since markets provided a framework within which mutually beneficial arrangements could be established without the need for bilateral negotiation. Hence in the longer term, as their institutions strengthen, developing countries may wish to move towards a more market-based approach to organizing their electricity systems in order to realize a greater share of the potential gains from trade in electricity.

The rest of the paper is organized as follows: Section 2 describes the setup; Section 3 considers cooperation that is facilitated by an independent cross-border system operator who observes production shocks in the connected power systems and Section 4 considers cooperation through a quasi-market.

2 Model

Two power systems, or players 1 and 2, are connected via an electricity interconnector with endogenous capacity K. Both systems have identical marginal costs of generation, which are normalized to zero.[10] Each power system operates close to full capacity with perfectly inelastic supply, which is subject to random production shocks. These shocks capture fluctuations in electricity production due to unexpected failures of generation units or unanticipated changes in the output of intermittent renewable generation such as wind or solar photovoltaics.[11] Thus, at time t, the domestic electricity production in

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[10] This assumption allows focusing on reducing the need for idle capacity as opposed to other potential benefits from power system integration. In real life situations, one would expect power systems to have different marginal costs of generation. These differences could arise because of idiosyncrasies in generation assets (e.g., fossil fuel fired power plants have higher marginal costs of generation than hydroelectric or nuclear power plants) or input subsidies, which are not uncommon in many developing countries. Billette de Villemeur and Pineau (2012) have shown that if marginal costs to generation are different, integrating power systems would still achieve the first best outcome absent other market distortions (e.g., environmental externalities). If one of the industries is regulated, productive inefficiencies could arise.

[11] The focus of the paper is on intraday exchange of electricity with an interconnector being used as a substitute for peaking generation capacity in the connected power systems. Examining the scope for cooperation on intraday basis is particularly important for developing countries, where traditionally short-term

power system i is $y_{i,t} = \bar{y} + \epsilon_{i,t}$, where $\bar{y}$ is a constant and $\epsilon_{i,t}$ are random variables with distribution that is symmetric around zero and has a discrete support

$$\left\{\epsilon^1, \epsilon^2, ..., \epsilon^S\right\},$$

where $\epsilon^s < \epsilon^{s+1}$ and $\bar{y} + \epsilon^1 \geq 0$. Negative values of ϵ^s represent unexpected outages, while positive values represent unexpected surges of output of renewable generation. Shocks $\epsilon_{i,t}$ are i.i.d. across time with $p^s := \mathbb{P}\left(\epsilon_{i,t} = \epsilon^s\right)$.[12] The aggregate supply $y_{1,t} + y_{2,t}$ is denoted by Y_t which may or may not be constant over time.

The random variable $\epsilon_t = (\epsilon_{1,t}, \epsilon_{2,t})$ captures the state of electricity production in period t.[13] All variables referring to state $\left(\epsilon^s, \epsilon^{s'}\right)$ have a superscript s, s', where $s,\ s' \in \{1, ..., S\}$. Thus, $\pi^{s,s'} := \mathbb{P}\left(\epsilon_{1,t} = \epsilon^s \cap \epsilon_{2,t} = \epsilon^{s'}\right)$ is the probability that state $\left(\epsilon^s, \epsilon^{s'}\right)$ is realized in period t. We assume that the joint distribution of production shocks is symmetric so that the probability of state (ϵ, ϵ') is equal to the probability of (ϵ', ϵ). This formulation of production shocks is capable of capturing various dependence structures.[14] Power system i has the instantaneous utility function $u_i(c)$, which is increasing, strictly concave and continuously differentiable in domestic electricity consumption with $\lim_{c \to 0} u_i'(c) = +\infty$.[15]

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trade contract were difficult to establish. For example, in the Southern African Power pool, bilateral trading agreements are long-term and are not flexible enough to accommodate varying demand profiles (Musaba 2009). Nevertheless, our model can also be applied to seasonal electricity exchange between power systems with different generation assets.

[12] This assumption is reasonable for most idiosyncratic shocks to electricity generation, however the model can be extended to accommodate for persistent shocks (such as e.g., longer periods of adverse weather conditions or technical failures). Key model propositions would qualitatively remain unchanged.

[13] We focus on the production side as electricity supply shocks are much more common in the developing countries. Typical demand side shocks are related to heating and cooling (air conditioning) processes, which are unaffordable for large size of developing country population and firms. The demand-side uncertainty can be easily incorporated by redefining ϵ_t as a net difference between supply and demand shocks.

[14] It is important, however, that the production shocks in the connected power systems are not perfectly positively correlated; otherwise whenever one power system experiences relatively low production, the other system also experiences low production and there is no scope for mutually beneficial electricity exchange. In such case of perfect positive correlation, welfare may be enhanced only through installing additional generation capacity.

[15] In addition, it is possible to normalize the utility function so that $u_i(\bar{y}) = 0$, $u_i(c) < 0$ for all $c < \bar{y}$ and $u_i(c) > 0$ for all $c > \bar{y}$, i.e., only consumption that exceeds the level $\bar{y}$ creates well-being, but when consumption falls below $\bar{y}$, the power system experiences disutility due to involuntary demand interruption. This normalization reflects the empirical evidence that overstretched power systems in many developing

From the perspective of a planner, at time t, the overall utility of a power system from the stream of future electricity consumption is given by

$$\mathbb{E}_t\left[\sum_{\tau=0}^{\infty}\beta^{\tau}u_i\left(c_{i,t+\tau}\right)\right],$$

where $\beta \in (0,1)$ is a discount factor and $\mathbb{E}_t[\cdot]$ is expectation operator conditional on information publicly available at t. The discount factor β can be viewed as being equal to $1/(1+r)$, where r is the discount *rate*[16] implied by the rate of time preference or by interest rate used to discount investment in the connected power systems. In addition to the usual effect of discounting the future, β could also capture an exogenous probability of terminating an ongoing cooperative relationship due to, e.g., political economy reasons in one of the countries that host the connected power systems. In this interpretation, each power system prefers early payoffs due the possibility that the cooperation may end before later payoffs can be collected. Since we view the interconnector as a substitute for peaking generation capacity capable of reacting rapidly to the current supply conditions, each period t should be viewed as being 'short' (that is, equivalent to hours, rather than months of the calendar time) and thus the relevant values of the discount factor are close to 1.

We consider a two-stage game where in the first stage, the planner chooses the size of interconnector's capacity K at cost $c(K)$, and in the second stage, the connected power systems engage in some electricity sharing arrangement. As the investment in large scale infrastructure projects (including interconnectors) in many developing countries becomes increasingly costly due to both institutional and financing constraints (Cavallo and Daude 2011, Majumdar and Chattopadhyay 2011), we assume that the cost $c(K)$ is an increasing, strictly convex and continuously differentiable function of K. The planner's objective is to maximize the long-run welfare resulting from the second-stage electricity sharing arrangement; the exact form of the planner's objective will depend on this second stage of the game.

For electricity sharing in the second-stage, we consider two alternative information struc-

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countries cannot produce sufficient amount of electricity to prevent involuntary interruption of demand.

[16] Thus a high discount factor β is equivalent to a low discount rate r.

tures. First, we assume that there is an independent cross-border system operator who observes and truthfully reveals production shocks in the connected power systems to all interested parties. Under the alternative scenario, each power system's production shocks are observed exclusively by that power system. This latter assumption is motivated by the fact that in practice, establishing a reliable monitoring institution is associated with significant costs and may not be feasible.

By entering an electricity sharing arrangement, when the installed interconnection capacity is K, the two power systems engage in an electricity exchange game with the following interaction in each period t. At the beginning of period t, the state variable $\epsilon_t = (\epsilon_{1,t}, \epsilon_{2,t})$ is realized. Then either the system operator reveals ϵ_t to both players or in the absence of the cross-border system operator, both power systems simultaneously announce their production shocks and their announcements result in the revealed state $\hat{\epsilon}_t = (\hat{\epsilon}_{1,t}, \hat{\epsilon}_{2,t})$. Finally, one of the power systems voluntarily transfers some non-negative amount of electricity that it generates to the other system;[17] the transfer results in the electricity consumption profile $(c_{1,t}, c_{2,t})$.

Let $h^t = \{\epsilon_\tau\}_{\tau=1}^{t}$ or $h^t = \{\hat{\epsilon}_\tau\}_{\tau=1}^{t}$ be the period-t history of state realizations (in presence of a system operator capable of monitoring production shocks) or revealed state realizations (when there is no system operator capable of monitoring), respectively. An electricity sharing arrangement, or a **contract,** is a sequence of functions $\left(c_1\left(h^t\right), c_2\left(h^t\right)\right)$, where $c_i\left(h^t\right)$ is player i's electricity consumption after the period-t history h^t. A contract induces an **allocation**, which is a stochastic process $\{(c_{1,t}, c_{2,t})\}_{t=1}^{\infty}$, where $c_{i,t}$ is period-t consumption of player i, $c_{i,t} = c_i\left(h^t\right)$. A **feasible allocation** must satisfy the resource constraints, for all t,

$$c_{1,t} + c_{2,t} \leq Y_t, \text{ and for all } i \ y_{i,t} + K \geq c_{i,t} \geq y_{i,t} - K,$$

according to which aggregate consumption cannot exceed aggregate production of electricity and electricity transfers cannot exceed the interconnector's capacity.

For a given K, there are two useful benchmarks to consider: autarky allocation and first-best efficient allocation.

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[17] Assuming that one player makes a transfer, while the other player makes no transfer is without loss of generality. Since smaller transfers pose less stringent incentive constraints than do larger ones, there is no need to consider cases in which the players make simultaneous transfers.

2.1 Autarky Allocation

The **autarkic allocation** $\{(y_{1,t}, y_{2,t})\}_{t=1}^{\infty}$, in which no power system ever makes positive transfers, results in a payoff of

$$\underline{v}_i = \frac{1}{1-\beta} \sum_{s=1}^{S} p^s u_i \left(\bar{y} + \epsilon^s\right) \tag{1}$$

to player i. Payoff $\underline{v}_i$ defines the reservation utility of power system i in any voluntary contract.

2.2 The First-Best Efficient Allocation

Consider a planner who, for a given K, aims to maximize the social surplus defined here as the discounted sum of the utilities of two power systems. It is assumed that the planner observes the realization of the state variable $\epsilon_t = (\epsilon_{1,t}, \epsilon_{2,t})$ in each period t.[18] The **first-best efficient contract** is a solution to the following optimization problem:

$$\begin{aligned}
\max_{\{c_{1,t}, c_{2,t}\}_{t=0}^{\infty}} \mathbb{E}_0 \left[\sum_{t=0}^{\infty} \beta^t \left(u_1\left(c_{1,t}\right) + \lambda_0 u_2\left(c_{2,t}\right)\right)\right] & \\
\text{s.t.} \sum_{i=1}^{2} c_{i,t} \leq Y_t \quad & \forall i, t \geq 0 \qquad (2) \\
y_{i,t} - K \leq c_{i,t} \leq y_{i,t} + K \quad & \forall i, t \geq 0 \qquad (3) \\
\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t u_i\left(c_{i,t}\right) \geq \underline{v}_i \quad & \forall i. \qquad (4)
\end{aligned}$$

where $0 \leq \lambda_0 \leq \infty$ is the relative Pareto weight of player 2 in the planner's objective. Weight λ_0 determines the distribution of payoffs across the two power systems. A utilitarian planner puts equal weight on the well-being of both players and sets $\lambda_0 = 1$, but asymmetric payoff distributions are also consistent with efficiency. In particular, by

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[18] As we are primarily concerned with finding the first-best efficient contracting solutions, we ignore possible market failures, such as e.g., externalities associated with electric power generation, in the social planner's problem. Billette de Villemeur and Pineau (2010) have shown that if these externalities are present connecting electricity systems can result in welfare losses.

changing λ_0 from 0 to ∞ it is possible to trace the entire Pareto frontier, with higher values of λ_0 corresponding to contracts in which player 2 gets more of the potential surplus from electricity exchange.

In the planner's problem, constraints (2) and (3) are feasibility constraints and constraint (4) ensures that ex ante each power system (weakly) prefers cooperation to autarky.

The planner's problem is well-behaved and thus has a solution. The planner can always choose the autarkic allocation, but in general, he can do better than that, because risk-averse players with concave instantaneous utility functions strictly prefer to smooth consumption over time as well as over states.

The solution to the planner's problem can be characterized as follows. Since the utility function of each power system is strictly increasing, the resource constraint (2) must be binding and at the optimum, $c_{1,t} + c_{2,t} = Y_t$ in every period. Moreover, since shocks $\epsilon_{i,t}$ are i.i.d. across time, the first-best efficient allocation must feature stationary consumption profiles. Then, the first order conditions of the planner's problem imply that in every period, the state-$\left(\epsilon^{\hat{s}}, \epsilon^{\hat{s}'}\right)$ consumption of player 2, $c^{\hat{s},\hat{s}'}$, satisfies

$$\frac{u_1'\left(Y^{\hat{s},\hat{s}'} - c^{\hat{s},\hat{s}'}\right)}{u_2'\left(c^{\hat{s},\hat{s}'}\right)} = \lambda_0 + \frac{\underline{\mu}^{\hat{s},\hat{s}'} - \bar{\mu}^{\hat{s},\hat{s}'}}{u_2'\left(c^{\hat{s},\hat{s}'}\right)}, \tag{5}$$

where $\underline{\mu}^{\hat{s},\hat{s}'}$ is the Lagrange multiplier associated with constraint

$$c^{\hat{s},\hat{s}'} \geq y_2^{\hat{s},\hat{s}'} - K \tag{6}$$

and $\bar{\mu}^{\hat{s},\hat{s}'}$ is the Lagrange multiplier associated with constraint

$$c^{\hat{s},\hat{s}'} \leq y_2^{\hat{s},\hat{s}'} + K. \tag{7}$$

Thus, the first-best efficient allocation features maximal insurance for both power systems against fluctuations in their electricity output. Consumption of each power system varies across states only insofar as there is uncertainty about the aggregate supply of electricity or the flows through the interconnector are capacity constrained. If there is no aggregate uncertainty and flows through the interconnector are never constrained, the efficient consumption profile features full-insurance with constant electricity consumption over time and across states. If there is aggregate uncertainty, but the interconnector capacity constraint is never binding, players smooth their consumption so as to keep the ratio of their marginal utilities constant and equal to λ_0 over time and across states. If the capacity constraint of the interconnector between the power systems is binding in some state $\left(\epsilon^{\hat{s}}, \epsilon^{\hat{s}'}\right)$, keeping the ratio of marginal utilities constant across states is no longer possible. In this case, the first-best efficient consumption profiles are still stationary, but the marginal utility ratio satisfies

$$\frac{u_1'\left(Y^{\hat{s},\hat{s}'} - c^{\hat{s},\hat{s}'}\right)}{u_2'\left(c^{\hat{s},\hat{s}'}\right)} > \lambda_0$$

whenever the interconnector capacity constraint restricts the electricity flows from player 2 to player 1 (i.e., constraint 6 binds), and

$$\frac{u_1'\left(Y^{\hat{s},\hat{s}'} - c^{\hat{s},\hat{s}'}\right)}{u_2'\left(c^{\hat{s},\hat{s}'}\right)} < \lambda_0$$

and whenever the interconnector capacity restricts the flows in the other direction (i.e., constraint 7 binds).

3 Cooperative Outcomes with Perfectly Observable Shocks

This section extends the efficient risk sharing framework with no commitment (among others, Thomas and Worrall (1988) and Kocherlakota (1996)) to model electricity sharing arrangements. To this end, we consider the situation when the implementation of the voluntary electricity sharing arrangements is facilitated by an independent system operator, which can perfectly observe production shocks in the connected power systems and on the basis of this information, recommend (in a non-binding manner) the appropriate dispatch.[19]

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[19] In our model, the only function of the independent system operator is coordination of cross-border electricity flows. In real world, independent system operators are more complex systems, which perform

The two-stage game described in Section 2 is solved in the reverse order, first establishing the equilibrium scope of electricity sharing arrangement, and then choosing the optimal size of interconnector's transmission capacity.

For a given K, the planer's problem in Section 2.2 ensures that each power system participating in an electricity sharing arrangement on average is at least as well off as under autarky. However, the solution to planner's problem does not guarantee that after *every* history of production shocks, it is in the interest of each power system to participate in the arrangement, rather than to renege on it. In reality, the scope for cooperation between power systems is limited by the two-sided lack of commitment, as at any moment, each power system may decide to default on its current electricity export obligations.

We assume that, if either party violates the contract, both power systems irrevocably revert to autarky. This assumption is consistent with viewing the electricity sharing arrangement as a subgame perfect equilibrium of an infinitely repeated game. In a one-shot interaction, making no transfer to the other system is a best response to any transfer choice of the opponent. Thus, the threat of reverting to autarky and never making any transfer is credible for any discount factor β. Moreover, since autarky provides less utility than any other feasible allocation that does not involve disposing of the produced electricity, reverting to autarky constitutes the most severe punishment that can be imposed on a deviant from an electricity sharing contract, i.e., it constitutes an optimal penal code in the sense of Abreu (1988). Thus, in the context of this paper, only those electricity sharing arrangements are **sustainable** which after any history of production shocks, provide each power system with a lifetime utility at least as high as its lifetime utility under autarky.[20]

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many other functions, such as e.g., maintaining transmission capacity and ensuring non-discriminatory access to the grid for individual generators (Sioshansi 2008, Pollitt 2012).

[20] In real world situations, it might be difficult or undesirable to commit to irrevocably break off cooperation upon the first non-compliance with the arrangement, particularly if setting up the infrastructure for cooperation requires significant pecuniary investment, such as investment in establishing an independent system operator, and non-pecuniary investment, such as investment in good-will building. Hence, the assumption that a breach of the contract triggers the permanent return to autarky may seem extreme. However, the results in this paper would not change qualitatively if a non-compliance was punished by a temporary reversion to autarky followed by an eventual return to electricity sharing (e.g., tit-for-tat strategy). It is even possible to design a contract such that, instead of the reversion to autarky, the punishment involves the point on the Pareto frontier for the current state which gives the autarky utility to the deviant power system (see, for example, Kletzer and Wright (2000)). Such contract would be weakly renegotiation-proof in the sense of Farrell and Maskin (1989).

An allocation is **(Pareto) optimal** if there exists no other feasible sustainable allocation which offers both power systems at least as much expected utility and one power system strictly more. Equivalently, an allocation is Pareto optimal if among all feasible allocations, it delivers to player 1 the largest expected utility for a given player 2's expected utility.

After characterizing the optimal sustainable electricity sharing agreement for a given K, we demonstrate that the optimal interconnector's capacity is increasing in β (Proposition 3). Intuitively, the predetermined risks of terminating the cooperative arrangement should be sufficiently low to justify an investment in interconnection; establishing physical connections between power systems does not suffice for establishing successful cross-border cooperation in environments with weak or non-existent contract enforcement institutions.

3.1 The Second Stage: The Optimal Electricity Sharing

We start by characterizing the optimal electricity sharing agreement that could emerge after the interconnector with capacity K has been installed. Following Thomas and Worrall (1988) approach, let $V^{\hat{s},\hat{s}'}(U)$ be the maximal utility of player 1 when the continuation utility promised to player 2 is U. $V^{\hat{s},\hat{s}'}(U)$ represents the Pareto frontier conditional on state $\left(\epsilon^{\hat{s}}, \epsilon^{\hat{s}'}\right)$. To characterize the frontier suppose that after observing the realization of the current-period production shocks, the planner chooses a consumption level c for player 2 and for every possible realization of production shocks in the next period, $\left(\epsilon^{s}, \epsilon^{s'}\right)$, a continuation utility $U^{s,s'}$ for player 2. Thus the system enters next period carrying a vector $\left[U^{1,1}, U^{1,2}, ..., U^{1,S}, U^{2,1}, U^{2,2}, ..., U^{S,S}\right]$ of contingent continuation utilities for player 2. Then the conditional Pareto frontier satisfies the following Bellman equation:

$$V^{\hat{s},\hat{s}'}(U) \quad = \max_{c,\left\{U^{s,s'}\right\}_{s,s'=1}^{S}} \left\{ u_1\left(Y^{\hat{s},\hat{s}'} - c\right) + \beta \sum_{s=1}^{S} \sum_{s'=1}^{S} \pi^{s,s'} V^{s,s'}\left(U^{s,s'}\right) \right\} \tag{8}$$

subject to

$$\lambda: \qquad u_2(c) + \beta \sum_{s=1}^{S} \sum_{s'=1}^{S} \pi^{s,s'} U^{s,s'} \geq U \tag{9}$$

$$\beta\pi^{s,s'}\eta_1^{s,s'}: \qquad V^{s,s'}\left(U^{s,s'}\right) \geq u_1\left(y_1^{s,s'}\right) + \beta \underline{v}_1 \; \forall \left(s,s'\right) \tag{10}$$

$$\beta\pi^{s,s'}\eta_2^{s,s'}: \qquad U^{s,s'} \geq u_2\left(y_2^{s,s'}\right) + \beta \underline{v}_2 \; \forall \left(s,s'\right) \tag{11}$$

$$\underline{\mu}: \qquad c \geq y_2^{\hat{s},\hat{s}'} - K \tag{12}$$

$$\bar{\mu}: \qquad c \leq y_2^{\hat{s},\hat{s}'} + K \tag{13}$$

The variable to the left of each constraint is the Lagrange multiplier associated with that constraint and will be used at a later stage. Constraint (9) states that the combination of his current consumption and his state-contingent future utility, $\left\{c, \left\{U^{s,s'}\right\}_{s,s'=1}^{S}\right\}$, must deliver to player 2 at least U, the utility level currently promised to him. The constraints (10) and (11) are forward-looking participation constraints for player 1 and 2, respectively. The participation constraints necessarily are forward looking as every time a power system is called upon to transfer electricity to another power system, it weighs the immediate cost of fulfilling this obligation against the future benefit from continuing cooperation. The feasibility constraints (12) and (13) ensure that the flows through the interconnector do not exceed its capacity. By assigning consumption $Y^{\hat{s},\hat{s}'} - c$ to player 1, when player 2 consumes c, the specification above implicitly incorporates the binding resource constraint (2).

Using arguments analogous to those of Thomas and Worrall (1988) and Ligon et al. (2002) it can be shown that the dynamic programming problem (8)-(13) is a concave problem for which the first-order conditions are necessary and sufficient.[21] In particular, it is easy to establish that the set of sustainable contracts is convex. This implies that in each state $(\hat{s}, \hat{s}')$, the set of sustainable discounted surpluses for each power system must be an interval. Let $\left[\underline{V}^{\hat{s},\hat{s}'}, \bar{V}^{\hat{s},\hat{s}'}\right]$ and $\left[\underline{U}^{\hat{s},\hat{s}'}, \bar{U}^{\hat{s},\hat{s}'}\right]$ denote such an interval for player 1 and player 2, respectively. The participation constraints of players imply that $\underline{V}^{\hat{s},\hat{s}'} = u_1\left(y_1^{\hat{s},\hat{s}'}\right) + \beta\underline{v}_1$ and $\underline{U}^{\hat{s},\hat{s}'} = u_2\left(y_2^{\hat{s},\hat{s}'}\right) + \beta\underline{v}_2$. Furthermore, the fact the total production in every period

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[21] For technical details, see Lemma 1 of Thomas and Worrall (1988).

is limited and preferences are non-satiated and represented by a strictly concave utility function implies that the Pareto-frontier $V^{\hat{s},\hat{s}'}(U)$ is decreasing, strictly concave and continuously differentiable on $\left[\underline{U}^{\hat{s},\hat{s}'},\bar{U}^{\hat{s},\hat{s}'}\right]$.

The first order conditions in conjunction with the Envelope theorem imply:

$$\begin{aligned} \frac{u_1'\left(Y^{\hat{s},\hat{s}'}-c\right)}{u_2'(c)} &= \lambda+\frac{\underline{\mu}-\bar{\mu}}{u_2'(c)} && (14)\\ \frac{\mathrm{d}V^{s,s'}}{\mathrm{d}U^{s,s'}} &= -\frac{\lambda+\eta_2^{s,s'}}{1+\eta_1^{s,s'}} && (15)\\ \frac{\mathrm{d}V^{\hat{s},\hat{s}'}}{\mathrm{d}U} &= -\lambda. && (16) \end{aligned}$$

According to the envelope condition (16), multiplier λ measures the rate at which player 1's utility can be traded off against the utility of player 2, conditional on the current state, i.e., λ is the relative Pareto weight of player 2. Once the next period's state is realized, the new value of λ is determined by (15). The current consumption profile of players is pinned down by equation (14), according to which λ is also equal to the ratio of the marginal utilities of consumption, subject to the interconnector capacity constraints being satisfied. Thus either there is a unique interior solution with the ratio of the marginal utilities equal to λ, or λ lies outside the set of marginal utility ratios which can be generated by feasible transfers in state $\left(\epsilon^s,\epsilon^{s'}\right)$. In the latter case, there is a corner solution with the entire interconnector capacity being utilized for transferring the maximal amount of electricity to one of the power systems. Hence, as in Ligon et al. (2002), the optimal contract is fully characterized by the evolution of λ.

Let $\lambda\left(h^t\right)$ be the value of λ at date t after the history h^t. Ligon et al. (2002) shows that $\lambda\left(h^t\right)$ satisfies a simple updating rule.

Proposition 1. *The optimal contract is fully characterized as follows: There exist* $S\times S$ *state dependent intervals* $\left[\underline{\lambda}^{s,s'},\bar{\lambda}^{s,s'}\right]$, $s,s'=1,2,...,S$, *such that* $\lambda\left(h^t\right)$ *evolves according to the fol-*

lowing rule. Let h^t be period-t history and let $\left(\epsilon^s, \epsilon^{s'}\right)$ be the state in period $t+1$, then

$$\lambda\left(h^{t+1}\right) = \begin{cases} \underline{\lambda}^{s,s'} & \text{if } \lambda\left(h^t\right) < \underline{\lambda}^{s,s'} \\ \lambda\left(h^t\right) & \text{if } \lambda\left(h^t\right) \in \left[\underline{\lambda}^{s,s'}, \bar{\lambda}^{s,s'}\right], \\ \bar{\lambda}^{s,s'} & \text{if } \lambda\left(h^t\right) > \bar{\lambda}^{s,s'} \end{cases} \tag{17}$$

where $\lambda\left(h^0\right) = \lambda_0$ is the initial value for the relative Pareto weight λ.

Proof. See proof of Proposition 1 in Ligon et al. (2002) □

Note that equation (14) is reminiscent of (5), i.e., if λ were not changing over time, the optimal contract would correspond to the first-best efficient contract. However, (15) shows that whether λ changes over time depends on whether or not the players' participation constraints are binding. In particular, every time that the participation constraint for player 2 is binding, his relative Pareto weight λ is increased; every time that the participation constraint of player 1 is binding, player 2's weight is reduced. This ensures that the power system with the binding participation constraint is promised a higher future electricity consumption stream.

The immediate corollary of Proposition 1 is that the distribution of relative Pareto weights, λ, converges weakly to a distribution that does not depend on the initial weight λ_0. This is because the λ-intervals do not vary with time and the probability of each production state is strictly positive and independent of time. The convergence of the distribution of λ implies that the distribution of per-period consumption profiles also converges.

Corollary 1. *The distribution of λ and thus also the distribution of per-period consumption profiles converge weakly to a unique invariant long-run distribution φ.*

Proposition 2 shows that the properties of the solution are such that for high discount factors first-best efficient allocations are sustainable, but for low discount factors the only sustainable allocation is autarkic. Moreover, for intermediate discount factors the optimal contract improves on autarky.

Proposition 2. *(i) There exists a critical* $0 < \bar{\beta} < 1$ *such that for all* $\beta \in \left(\bar{\beta}, 1\right)$*, there is some first-best efficient contract which is sustainable; (ii) there exists a critical* $1 > \underline{\beta} > 0$ *such that for all* $\beta \in \left(0, \underline{\beta}\right)$*, there is no non-autarkic sustainable contract; (iii) for* $\beta \in \left(\underline{\beta}, \bar{\beta}\right)$*, the optimal contract improves on autarky, but is not first-best efficient. Moreover, welfare improvement of an optimal contract is continuous in* β*.*

Proof. (i) The critical $\bar{\beta} < 1$ exists by the Folk theorem for infinitely repeated games with varying states.

(ii) It is clear that when $\beta = 0$, the only sustainable contract is autarkic. Proposition 2 (v) in Ligon et al. (2002) shows that also for a sufficiently small, but strictly positive β, power systems make no transfers to each other in an optimal contract.

(iii) Let $\zeta^{s,s'} \equiv u_1' \left(\bar{y} + \epsilon^s\right) / u_2' \left(\bar{y} + \epsilon^{s'}\right)$ be the autarkic ratio of marginal utilities in state $\left(\epsilon^s, \epsilon^{s'}\right)$, where each power system consumes all electricity it produces. By Proposition 2 (iv) in Ligon et al. (2002), for each state $\left(\epsilon^s, \epsilon^{s'}\right)$, $\zeta^{s,s'} \in \left[\underline{\lambda}^{s,s'}, \bar{\lambda}^{s,s'}\right]$, i.e., each λ interval contains the associated autarkic ratio of marginal utilities. Moreover, $\min_{s,s'} \left\{\underline{\lambda}^{s,s'}\right\} = \min_{s,s'} \left\{\zeta^{s,s'}\right\}$ and $\max_{s,s'} \left\{\bar{\lambda}^{s,s'}\right\} = \max_{s,s'} \left\{\zeta^{s,s'}\right\}$ and, for any state $(\hat{s}, \hat{s}')$ that is not associated with the extremal marginal utility ratios, $\min_{s,s'} \left\{\zeta^{s,s'}\right\}$ or $\max_{s,s'} \left\{\zeta^{s,s'}\right\}$, the autarkic marginal utility ratio $\zeta^{\hat{s},\hat{s}'}$ is contained in the interior of the λ interval $\left[\underline{\lambda}^{\hat{s},\hat{s}'}, \bar{\lambda}^{\hat{s},\hat{s}'}\right]$. This implies that when $\bar{\beta} > \beta > \underline{\beta}$ and the λ intervals contain more than a single point, but do not all overlap, a power system with the binding participation constraint is making an electricity transfer. In an optimal contract, λ follows updating rule (17) and thus in the long-run, it takes values only in the set $\left\{\underline{\lambda}^{s,s'}, \bar{\lambda}^{s,s'}\right\}_{s,s'=1}^{S}$. This implies that participation constraints are binding infinitely often and consequently also electricity transfers are made infinitely often in any optimal contract. Since making no transfers is always possible, the optimal electricity transfers must be weakly improving on autarky. Furthermore, by Proposition 2 (vi) in Ligon et al. (2002), each $\underline{\lambda}^{s,s'}$ and $\bar{\lambda}^{s,s'}$ is continuous in β. Thus also the electricity transfers are continuous in β, leading to a continuous welfare improvement. □

3.2 The First Stage: The Optimal Interconnector's Capacity

In this stage, a social planner chooses the size of interconnector's capacity through maximizing long-run welfare:

$$\max_{K} \frac{1}{1-\beta} \mathbb{E}_{\varphi} \left[\tilde{u}_1 (\beta, K) + \tilde{u}_2 (\beta, K) \right] - c(K), \tag{18}$$

where $\tilde{u}_1(\beta, K)$ and $\tilde{u}_2(\beta, K)$ are the stochastic per-period utilities of player 1 and 2, respectively, in the long-run of sustainable electricity sharing arrangement; expectation is taken with respect to φ, the long-run invariant distribution of the per-period utility levels (see Corollary 1). The planner's objective does not take into account the transition period during which the distribution of per-period consumption profiles converges to φ. This implicitly assumes that β is high and thereby welfare during the transition period is unimportant relative to the long-run welfare.

The planner's objective also side-steps the issue of sharing the cost of interconnection by power systems. As long as interconnector capacity K is chosen to maximize total welfare net of costs, there is a multitude of ways to share the interconnection costs and the exact cost sharing agreement may depend on the relative bargaining powers of the parties. For example, 'fair' division of costs implies that the costs are split proportionally to the derived benefit, that is each power system i covers proportion

$$\theta_i \equiv \frac{\mathbb{E}_{\varphi} \left[\tilde{u}_i (\beta, K) \right] - (1-\beta) \underline{v}_i}{\mathbb{E}_{\varphi} \left[\tilde{u}_1 (\beta, K) + \tilde{u}_2 (\beta, K) \right] - (1-\beta) \left(\underline{v}_1 + \underline{v}_2 \right)}$$

of costs. The denominator of θ_i is the increase in the expected per period utility of power system i due to cross-border cooperation; the numerator of θ_i is the total increase in per period expected welfare.

Recall that in the sustainable electricity sharing agreement, the current electricity consumption profile of players is determined by (14), according to which λ is equal to the ratio of the marginal utilities of consumption, whenever the interconnector capacity constraints do not bind. Furthermore, the interconnector's capacity does not affect the evolution or the long-run distribution of λ, φ. Let $\bar{K}(\beta)$ denote the maximal electricity transfer as implied by the long-run distribution of λ, that is, when $K = \bar{K}(\beta)$, the transmission constraints never bind in the long-run. $\bar{K}(\beta)$ is well defined as φ has a finite support. It never pays to expand interconnector's capacity beyond $\bar{K}(\beta)$, and the optimal interconnector's capacity $K^*(\beta)$ belongs to the interval $[0, \bar{K}(\beta)]$.

The interior solution for an optimal interconnector's capacity satisfies the first order condition:

$$\frac{\mathrm{d}}{\mathrm{d}K}\left(\frac{1}{1-\beta}\mathbb{E}_{\varphi}\left[\tilde{u}_1(\beta, K) + \tilde{u}_2(\beta, K)\right]\right) = c'(K). \tag{19}$$

When $0 \leq K < \bar{K}(\beta)$, the left hand side of (19) is strictly positive. This is because the interconnector transmission constraints sometimes bind and the ratio of the marginal utilities of consumption departs from λ. Indeed, by the Envelope theorem applied to the Bellman equation (8),

$$\frac{\mathrm{d}V^{\hat{s},\hat{s}'}}{\mathrm{d}K} = \underline{\mu} + \bar{\mu} \geq 0,$$

where inequality is strict when either constraint (12) or constraint (13) binds. This indicates that the social surplus generated by an optimal sustainable contract is strictly increasing in K when interconnector's capacity constraint binds in some state.

The right hand side of (19) is also strictly positive for $K > 0$, and nonnegative for $K = 0$ (by our assumption in Section 2). If $c'(0) = 0$, then the optimal capacity level $K^*(\beta) > 0$ for all $\beta > \underline{\beta}$, where $\underline{\beta}$ is the critical level of β defined in Proposition 2 (ii) such that for all $\beta \leq \underline{\beta}$ only the autarkic contract is sustainable; if $c'(0) > 0$, $K^*(\beta)$ may be equal to 0 for some $\beta > \underline{\beta}$.

The discussion above acknowledges that the optimal interconnector's capacity depends on the discount factor β. The discussion following Proposition 2 highlights that for low values of β, the binding participation constraints of power systems limit the optimal sustainable electricity transfers, but as β increases, the participation constraints get relaxed and optimal electricity transfers increase. This suggests that the optimal interconnector's capacity is also increasing in β. Furthermore, as β approaches 1, the left hand side of (19) goes to infinity whenever marginal benefit of additional capacity is positive in at least one state in the support of φ. Hence, for sufficiently high β, $K^*(\beta) = \bar{K}(\beta)$.

Proposition 3 summarizes the discussion in this section.

Proposition 3. *(i) There exists a critical* $1 > \tilde{\beta} \geq \underline{\beta}$ *such that for all* $\beta \in [0, \tilde{\beta}]$, $K^*(\beta) = 0$; *(ii)* *there exists a critical* $1 > \hat{\beta} > \tilde{\beta}$ *such that for all* $\beta \in \left[\hat{\beta}, 1\right]$, $K^* (\beta) = \bar{K} (\beta)$; *(iii) for* $\beta \in \left(\tilde{\beta}, \hat{\beta}\right)$, $K^* (\beta) \in (0, \bar{K} (\beta)]$ *and* $K^* (\beta)$ *is weakly increasing in* β.

3.3 Numerical Example

To illustrate key properties of the model we consider a simple example, where production shocks of the two power systems are perfectly negatively correlated and there is no aggregate uncertainty.[22] We assume that the power systems have identical preferences represented by the logarithmic utility function $u_i (\cdot) = \ln (\cdot)$ for $i = 1, 2$ and that the capacity constraint of the interconnector is never binding. Suppose that the production shocks of each power system are independent across time and can take three values $\{-\epsilon, 0, \epsilon\}$. In every period, the production of the two power systems sums up to $Y = 2\bar{y}$, which implies that there are three states hl, lh and mm with production levels $(\bar{y} + \epsilon, \bar{y} - \epsilon)$, $(\bar{y} - \epsilon, \bar{y} + \epsilon)$ and $(\bar{y}, \bar{y})$, respectively. Suppose that states hl and lh occur with probability $p (1 - p)$ each and state mm occurs with probability $1 - 2p (1 - p)$, where $p \in (0, 1)$.

In this setting the first-best contract results in full insurance for both players with electricity consumption not varying across time and states. Thus, if ex ante the two players have equal weights in the social planner's objective, i.e., $\lambda_0 = 1$, the first-best outcome involves electricity consumption of $\bar{y}$ in every period for every player. This outcome can be achieved through a transfer of ϵ from player 1 to player 2 in state hl and a transfer of the same magnitude in opposite direction in state lh. Such transfers are self-enforcing if the participation constraint of the power system that is required to make an electricity transfer is satisfied, i.e., if

$$\frac{u (\bar{y})}{1 - \beta} \geq u (\bar{y} + \epsilon) + \beta \underline{v}, \tag{20}$$

where $\underline{v}$ is the autarkic lifetime utility defined in (1).

In terms of characterization of the optimal contract described in Proposition 1, there is an interval of relative Pareto weights λ corresponding to each state hl, lh and mm. Proof of Proposition 2 implies that with logarithmic utility $\underline{\lambda}^{hl} = (\bar{y} - \epsilon) / (\bar{y} + \epsilon)$ and $\bar{\lambda}^{lh} = (\bar{y} + \epsilon) / (\bar{y} - \epsilon)$. Moreover, since the setup is symmetric, it must be the case that $\bar{\lambda}^{hl} =$

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[22] This example is close in spirit to the example in Ligon et al. (2002).

$1/\underline{\lambda}^{lh}$ and $\bar{\lambda}^{mm} = 1/\underline{\lambda}^{mm}$. Thus, to obtain the complete characterization of the optimal contract, we only need to determine $\underline{\lambda}^{lh}$ and $\underline{\lambda}^{mm}$. There are three cases that need to be considered separately: (1) the λ intervals are disjoint; (2) intervals $\left[\underline{\lambda}^{hl}, \bar{\lambda}^{hl}\right]$ and $\left[\underline{\lambda}^{lh}, \bar{\lambda}^{lh}\right]$ each overlap with $\left[\underline{\lambda}^{mm}, \bar{\lambda}^{mm}\right]$, but not with each other; and (3) all three intervals have some points in common. In each of these cases, (17) determines the evolution of λ.[23]

Participation constraint (20) defines a critical discount factor $\bar{\beta}$ such that for all $\beta \geq \bar{\beta}$, all three λ intervals have at least one point in common. In particular, $\lambda_0 = 1$ for sure belongs to the overlap region, and thus λ never changes from its initial value and electricity transfers achieve full insurance with each power system consuming $\bar{y}$ in every period and every state.[24] By proposition 2, when $\beta \leq \underline{\beta}$, no non-autarkic contract is sustainable. Hence, in each state each power system consumes what it produces. In the intermediate range of β, the optimal contract is a compromise between the first-best and the autarkic contract. To see this suppose that $\underline{\beta} < \beta < \bar{\beta}$ and continue to assume that $\lambda_0 = 1$. In this case, each power system initially consumes $\bar{y}$ in state (m, m). However, once state hl or state lh is realized, the power system first to receive a bad shock becomes a 'debtor' who promises the 'creditor' power system a higher expected electricity consumption stream in future.

Figure 1a illustrates the scope for the optimal contract to improve on autarky, when $\bar{y} = 100$, $\epsilon = 15$ and $p = 0.2$.[25] In the figure, all utilities are expressed in per-period terms

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[23] In each of these cases, $\underline{\lambda}^{lh}$ and $\underline{\lambda}^{mm}$ can be obtained through the following three-step procedure. First, starting from an end-point of a λ interval, the evolution of λ described in Proposition 1 allows expressing the discounted life-time utility of each power system in terms of current period utility and continuation discounted life-time utilities starting from various end-points of λ intervals. Solving the system of thus obtained simultaneous equations, it is possible to obtain all relevant discounted life-time utilities in terms of current period utilities in different states. Then the first order condition (14) can be used to express these current period utilities as functions of λ's. Finally, binding participation constraints of power system 2 in states lh and mm can be used to solve for $\underline{\lambda}^{lh}$ and $\underline{\lambda}^{mm}$ as required.

[24] Since in any asymmetric efficient allocation one of the power systems is strictly worse off than in the symmetric efficient allocation, the participation constraint of the exporting power system is satisfied for the largest set of discount factors when $c_1^{s,s'} = c_2^{s,s'} = Y^{s,s'}/2$, where $Y^{s,s'}$ is the aggregate production in state $\left(\epsilon^s, \epsilon^{s'}\right)$. Hence, when $\beta = \bar{\beta}$, the equal-payoff contract is the only sustainable first-best efficient contract. The set of sustainable first-best efficient electricity sharing arrangements expands as β increases.

[25] There is a significant variation in reliability of power supply in developing countries. The numbers from numerical example are roughly illustrative of the current state of power supply in better developed countries of Sub Saharan Africa (e.g., Kenya), where transmission and distribution losses account for about 15% of total generation (based on EIA International Energy Statistics database, `http://www.eia.gov/beta/`

through multiplying the corresponding life-time utility by $(1-\beta)$. The calculations underlying the figure show that for $\beta \leq \underline{\beta} = 0.914$, the λ intervals are degenerate and only autarkic outcome is sustainable. Hence, for this range of β, when interconnection is costless, the per-period expected utility of a power system participating in the optimal contract with $\lambda_0 = 1$ coincides with the expected per-period utility in autarky (represented by the straight dotted line at the bottom of the figure). For $\beta \geq \beta^* = 0.975$, all three λ intervals have points in common and the first-best symmetric payoff is sustainable. So in the figure, the per-period expected utility of a power system in the optimal symmetric contract with costless interconnection coincides with the symmetric first-best per-period utility (represented by the straight dotted line at the top of the figure). For $\beta \in (0.914, 0.975)$, the optimal contract improves on autarky, but is not first-best efficient. In particular, for $\beta \in (0.914, 0.955)$, the λ intervals have non-empty interiors, but are disjoint and for $\beta \in [0.955, 0.975)$, intervals $\left[\underline{\lambda}^{hl}, \bar{\lambda}^{hl}\right]$ and $\left[\underline{\lambda}^{lh}, \bar{\lambda}^{lh}\right]$ each overlap with $\left[\underline{\lambda}^{mm}, \bar{\lambda}^{mm}\right]$, but not with each other. In the figure, for $\beta \in (0.914, 0.975)$, the expected utility in the optimal contract is increasing in β and lies between the expected utility in autarky and the symmetric first-best utility.

Costly interconnection does not affect evolution of the λ intervals, but reduces the scope for consumption smoothing. Hence, when interconnection is costly, the long-term welfare in the optimal contract with endogenous capacity is lower than in the optimal contract with costless interconnection. Figure 1b also demonstrates that the optimal interconnector's capacity increases in the discount factor β.

4 Cooperative Outcomes with Privately Observable Shocks

In Section 3 we showed that long-term cooperative arrangements can deliver some benefits of connecting power systems when power systems are sufficiently patient. However, the analysis relied crucially on the assumption that there is an independent system operator who can perfectly observe production shocks in the connected regions. In practice, establishing such a monitoring institution is associated with significant costs, especially

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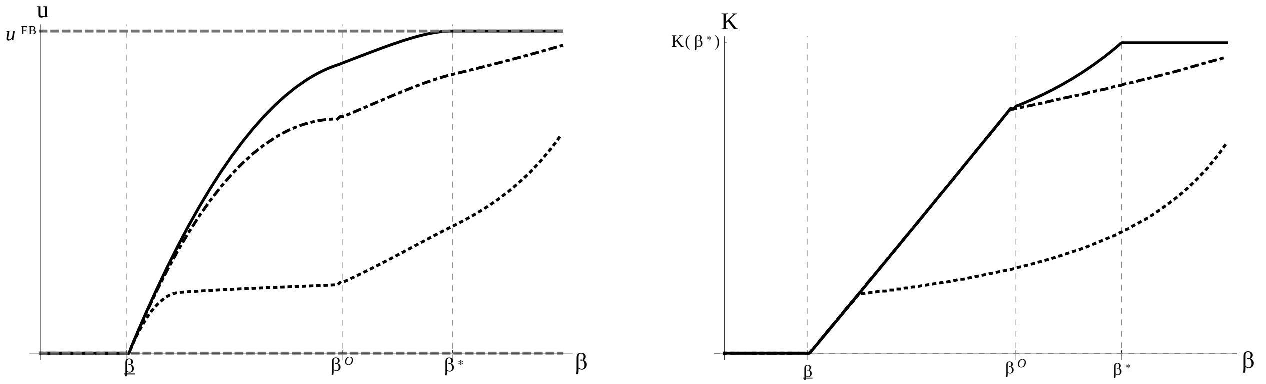
`international/`) and occur with about 20% probability (i.e., 6 days in a typical month, based on World Bank WDI database, `http://data.worldbank.org/`).



(a) The per-period expected payoff of a power system participating in the optimal contract with $\lambda_0 = 1$ net of interconnection costs.

(b) The optimal interconnection capacity: The top mark on vertical axis corresponds to the maximal electricity transfer in the first best contract, $\bar{K}(\beta^*) = \epsilon$.

Figure 1: The per-period expected payoff and interconnection capacity in the optimal contract as a function of discount factor β, when $\bar{y} = 100$, $\epsilon = 15$, $p = 0.2$ and interconnection costs are of the form $c(K) = aK^2$. In both figures, the solid black line corresponds the optimal contract when interconnection is costless; the dash-dotted line corresponds to the optimal contract with $c(K) = 0.0002K^2$; the dotted line corresponds to the optimal contract with $c(K) = 0.002K^2$.

in developing countries. Moreover, even if such operator exists, it cannot always discover the true nature of production shocks. For instance, it is very difficult to establish whether a decrease in electricity production is due to a genuine outage or is a result of strategic manipulation of generators (Fogelberg and Lazarczyk 2014). This suggests that in reality power system's production shocks are likely to be observed exclusively by that power system.

If production shocks in the connected power systems are not perfectly observable by all parties, welfare gains that could be realized through an electricity sharing arrangement are lower relative to the case of no information asymmetries. This is because to avoid exporting electricity, each power system is tempted to misreport its supply conditions when current production is relatively high, but this cannot be observed by the other party. To create sufficient incentives for truthful revelation of the production shocks, in addition to participation constraints, also incentive compatibility constraints must be satisfied in every period. These additional constraints should ensure that demanding an electricity transfer from the other party in the current period is punished by lower expected future electricity imports, or, equivalently, exporting electricity in the current period is rewarded by higher expected electricity imports in future.[26]

The importance of incentive compatibility constraints in models with privately observed random shocks has been long recognized. For example, Atkeson and Lucas (1992) study optimal consumption smoothing in an economy with large number of consumers who privately observe taste shocks affecting their marginal utility of current consumption, while Thomas and Worrall (1990) study optimal lending agreements in a model where a risk averse borrower is privately informed of his income shocks. However, these papers assume full commitment, i.e., players are committed to the contract signed at the beginning

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[26] Under perfect monitoring of shocks, a negative production shock also results in a reduction of current and future electricity consumption, when discount factor β is relatively low and the participation constraint of the exporting power system is binding. However, the optimal electricity sharing arrangement is always forward looking as each power system is willing to fulfill its current export obligation as long as it expects sufficient benefits from continuing cooperation in the future. In contrast, with unobservable production shocks, the reduction in future expected electricity consumption following a run of low production reports is a *retrospective* disciplining device that ensures truthful reporting of shocks. For example, results from Hertel (2004) suggest that in an optimal electricity sharing arrangement with unobservable production shocks, electricity consumption should strictly decrease over time for a power system that is repeatedly hit by an unfavorable production shock even when no participation constraints are binding.

and cannot walk away from it at the later date. More recently Hertel (2004) characterizes optimal risk sharing in a model with two players, who can opt out of the agreement at any time and where one agent's stochastic income realizations are his private information. While Hertel (2004) is relevant for modeling cooperation between connected power systems, deriving full characterization of an electricity sharing contract with unobservable production shocks is beyond the scope of our paper. Instead, we argue that a quasi-market for excess electricity is a simple way to achieve some cooperation when production shocks are privately observed by each power system.

The quasi-market relies on a "chip mechanism". In this mechanism, the connected power systems are endowed with a certain number of megawatt chips. The chips can only be used to keep track of electricity import/export imbalance between the parties to the contract and are worthless outside the cooperative relationship. When power system *i* exports electricity to power system *j* and *j* owns some chips, *j* gives chips to *i* in exchange for electricity. When one of the power systems has all of the available chips, it stops exporting electricity to the other system until the other system has earned back some chips.[27] Note that when the number of chips becomes sufficiently large, their interpretation becomes close to the scarcity prices that are used to clear cross-border electricity markets in developed countries (e.g., Nordpool) when the aggregate supply of electricity is tight. However, a mechanism to provide real-time scarcity prices that can then feed back into spot and contract markets requires a properly incentivized cross-border independent system operator (Newbery 2009). When this institutional setup is not possible to achieve (i.e., the scenario considered in this section) scarcity prices will fail clearing the market due to information asymmetry.

Given the complexity of characterizing equilibria in the electricity sharing contract with unobservable production shocks, we consider a simplified case of the model presented in Section 2, where production shocks are independent across the power systems and across time and can take two values $-\epsilon$ and $+\epsilon$ with $\mathbb{P}(\epsilon_t = -\epsilon) = p$. In this context, suppose that each player is privately informed of the realization of its current production shock

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[27] Möbius (2001) and Hauser and Hopenhayn (2008) study chip mechanism in the context of continuous-time repeated favor-exchange game; there is also a rich literature on favor exchange in discrete time (see e.g., Nayyar 2009, Kalla 2010, Abdulkadiroglu 2013, Abdulkadiroglu and Bagwell 2012). Olszewski and Safronov (2012) study chip strategies in repeated oligopoly games, in which firms privately observe their costs of production.

and the predetermined interconnector's capacity is $K \leq \epsilon$. Consider the chip mechanism with N chips that fully utilizes the interconnector's capacity, the **N-chip K-capacity mechanism**. In this mechanism, whenever a power system holding some chips experiences a negative production shock, but the other power system has high production, the power system with low current production receives an electricity transfer of K in exchange for a chip. Because both power systems can simultaneously experience a positive or a negative production shock, this set up is a generalization of a chip mechanism in the context of favor trading studied by Abdulkadiroglu and Bagwell (2012).

Let V_n^N, $n = 0, 1, ..., N$ denote a player's expected discounted payoff in the N-chip mechanism when he holds n chips. Then the N-chip mechanism delivers the following payoffs: for $n = 1, ..., N-1$

$$\begin{aligned} V_n^N &= p^2 \left(u\left(\bar{y}-\epsilon\right) + \beta V_n^N \right) + p\left(1-p\right) \left(u\left(\bar{y}-\epsilon+K\right) + \beta V_{n-1}^N \right) \\ &\quad + p\left(1-p\right) \left(u\left(\bar{y}+\epsilon-K\right) + \beta V_{n+1}^N \right) + \left(1-p\right)^2 \left(u\left(\bar{y}+\epsilon\right) + \beta V_n^N \right) \end{aligned} \tag{21}$$

and at the boundary

$$\begin{aligned} V_0^N &= p^2 \left(u\left(\bar{y}-\epsilon\right) + \beta V_0^N \right) + p\left(1-p\right) \left(u\left(\bar{y}-\epsilon\right) + \beta V_0^N \right) \\ &\quad + p\left(1-p\right) \left(u\left(\bar{y}+\epsilon-K\right) + \beta V_1^N \right) + \left(1-p\right)^2 \left(u\left(\bar{y}+\epsilon\right) + \beta V_0^N \right) \end{aligned} \tag{22}$$

$$\begin{aligned} V_N^N &= p^2 \left(u\left(\bar{y}-\epsilon\right) + \beta V_N^N \right) + p\left(1-p\right) \left(u\left(\bar{y}-\epsilon+K\right) + \beta V_{N-1}^N \right) \\ &\quad + p\left(1-p\right) \left(u\left(\bar{y}+\epsilon\right) + \beta V_N^N \right) + \left(1-p\right)^2 \left(u\left(\bar{y}+\epsilon\right) + \beta V_N^N \right). \end{aligned} \tag{23}$$

By Lemma 1 in Abdulkadiroglu and Bagwell (2012), this system of equations has a unique solution $\left\{V_n^N\right\}_{n=0}^N$, where $V_n^N < V_{n+1}^N$ for all $n = 0, ..., N-1$.

Each power system wants to participate in the mechanism if its participation constraint is satisfied, i.e., it must be the case that for $n = 0, ..., N$,

$$V_n^N \geq \underline{v},$$

where $\underline{v}$ is defined in (1) and represents the minimum lifetime utility that each player can guarantee himself in autarky.

In addition, to induce the power system with a positive production shock to report its production truthfully, the mechanism must satisfy the following incentive compatibility constraints: for $n = 1, ..., N - 1$

$$\begin{aligned} p\left(u\left(\bar{y}+\epsilon-K\right)+\beta V_{n+1}^{N}\right) \quad &+ \quad (1-p)\left(u\left(\bar{y}+\epsilon\right)+\beta V_{n}^{N}\right) \\ \geq p\left(u\left(\bar{y}+\epsilon\right)+\beta V_{n}^{N}\right) \quad &+ \quad (1-p)\left(u\left(\bar{y}+\epsilon+K\right)+\beta V_{n-1}^{N}\right) \end{aligned} \tag{24}$$

and at the boundary

$$p\left(u\left(\bar{y}+\epsilon-K\right)+\beta V_{1}^{N}\right)+(1-p)\left(u\left(\bar{y}+\epsilon\right)+\beta V_{0}^{N}\right) \quad \geq \quad u\left(\bar{y}+\epsilon\right)+\beta V_{0}^{N} \tag{25}$$

$$p\left(u\left(\bar{y}+\epsilon\right)+\beta V_{N}^{N}\right)+(1-p)\left(u\left(\bar{y}+\epsilon+K\right)+\beta V_{N-1}^{N}\right) \quad \leq \quad u\left(\bar{y}+\epsilon\right)+\beta V_{N}^{N}. \tag{26}$$

The constraint (25) ensures that the player holding no chips wants to reveal high production levels, despite the possibility that with probability $(1 - p)$ the opponent will request an electricity transfer from him in exchange for a chip. The constraint (26) ensures that the current holder of all chips will want to reveal high production levels, forgoing an electricity transfer from the opponent that would increase the current electricity consumption to $\bar{y} + \epsilon + K$ if the opponent's production level also turns out to be high. The constraint (24) ensures that the player holding n chips wants to reveal high production levels, despite facing both the temptation of a player with no chips and the temptation of a player with all the chips.

Finally, the power system with a negative production shock will report its production truthfully if the following incentive compatibility constraints hold: for $n = 1, ..., N - 1$

$$\begin{aligned} p\left(u\left(\bar{y}-\epsilon+K\right)+\beta V_{n-1}^{N}\right) \quad &+ \quad (1-p)\left(u\left(\bar{y}-\epsilon\right)+\beta V_{n}^{N}\right) \\ \geq p\left(u\left(\bar{y}-\epsilon\right)+\beta V_{n}^{N}\right) \quad &+ \quad (1-p)\left(u\left(\bar{y}-\epsilon-K\right)+\beta V_{n+1}^{N}\right) \end{aligned} \tag{27}$$

and at the boundary

$$p\left(u\left(\bar{y}-\epsilon\right)+\beta V_{0}^{N}\right)+(1-p)\left(u\left(\bar{y}-\epsilon-K\right)+\beta V_{1}^{N}\right) \quad \leq \quad u\left(\bar{y}-\epsilon\right)+\beta V_{0}^{N} \tag{28}$$

$$p\left(u\left(\bar{y}-\epsilon+K\right)+\beta V_{N-1}^{N}\right)+(1-p)\left(u\left(\bar{y}-\epsilon\right)+\beta V_{N}^{N}\right) \quad \geq \quad u\left(\bar{y}-\epsilon\right)+\beta V_{N}^{N}. \tag{29}$$

The constraint (28) ensures that the player holding no chips wants to reveal low production levels and receive no chip for sure. The constraint (29) ensures that the current holder of all chips wants to reveal low production levels, thereby probabilistically increasing its current electricity consumption, but giving up a claim on the future consumption in the form of a chip. The constraint (27) ensures that the player holding n chips wants to reveal low production levels and probabilistically give up a chip instead of earning a chip.

A chip mechanism satisfying constraints (24)-(29) is called *incentive compatible.*

Proposition 4 shows that for high discount factors, there is an incentive compatible N-chip K-capacity mechanism that improves on autarky, but even the best incentive compatible K-capacity chip mechanism delivers payoffs lower than in the case of publicly observable production shocks. When β is high, the main cause of inefficiency in the chip mechanism is accumulation of chips in the hands of one party. The power system holding all chips stops exporting electricity until it receives some electricity imports. This implies that cooperation partially breaks down when one of the power systems is subject to a prolonged run of negative production shocks and is unable to export any electricity. For lower values of β, a K-capacity chip mechanism also fails to adjust the magnitude of the required electricity transfers in an optimal manner.

Proposition 4. *There exists a critical* $0 < \beta^* < 1$ *such that for all* $\beta \in (\beta^*, 1)$*, there exists an incentive compatible K-capacity chip mechanism. Any incentive compatible K-capacity chip mechanism improves on autarky, but yields a payoff that is lower than the payoff in the optimal symmetric contract with observable production shocks (i.e., the contract with* $\lambda_0 = 1$*).*

Proof. Consider the chip mechanism with one chip.[28] In this mechanism, the only binding constraint is the incentive constraint of the player with positive production shock and with no chips, (25). This constraint implies (26) (by strict concavity of the utility function $u(\cdot)$) as well as the participation constraints of the power systems, which, in turn, imply incentive compatibility constraints of the player with a negative production shock, (28) and (29). Hence, by rearranging (25) it is possible to obtain a critical discount factor $\beta^* < 1$ such that for all $\beta \geq \beta^*$ the one-chip K-capacity mechanism is incentive compatible. This

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[28] This mechanism corresponds to the *simple EM relationship* of Abdulkadiroglu and Bagwell (2012).

mechanism improves upon autarky as players make positive electricity transfers thereby achieving some electricity consumption smoothing.

Consider an incentive compatible K-capacity chip mechanism and compare it to the optimal contract with observable production shocks described in Section 3. If $\underline{\beta} < \beta < \bar{\beta}$, the optimal contract requires transfers in states with symmetric as well as asymmetric production distribution, even though there are no a priori restrictions on admissible transfers. In any K-capacity chip mechanism, however, players make transfers only in asymmetric production states. Consequently, in this range of β, any incentive compatible chip mechanism must yield lower life-time utility to players than the optimal contract. Suppose $\beta \geq \bar{\beta}$. For this range of β, the optimal contract with $\lambda_0 = 1$ requires transfers of size ϵ only in asymmetric production states. Moreover, since the contract is forward looking, there is no upper bound on the number of transfers a player makes before receiving a transfer back. In any incentive compatible chip mechanism, however, the number of chips must be finite. Moreover, since production shocks are iid, a history of shocks which requires a player to make more than N consecutive transfers can occur with a strictly positive probability. In this case, one of the players accumulates all the chips, upon which he makes no more electricity transfers until the other player earns some chips back by exporting electricity. Thus, even if $K = \epsilon$, an incentive compatible chip mechanism delivers less than maximal insurance and yields payoffs lower than the payoffs in the optimal contract with observable production shocks. □

In an N-chip mechanism, incentive compatibility constraints of the power system experiencing a negative production shock, (27)-(29), are implied by the participation constraints and hence can be ignored. Combining (25) with (22), it can also be verified that (25) implies that $V_0^N \geq \underline{v}$ and also $V_n^N \geq \underline{v}$, because $V_n^N < V_{n+1}^N$ for $n = 0, ..., N-1$. Consequently, the incentive compatibility constraint of the power system holding no chips and experiencing a positive production shock implies all the participation constraints. Furthermore, adapting arguments in Lemma 6 of Abdulkadiroglu and Bagwell (2012), it can be shown that condition

$$\beta \left[V_N^N - V_{N-1}^N \right] \geq u \left(\bar{y} + \epsilon \right) - u \left(\bar{y} + \epsilon - K \right) \tag{30}$$

is sufficient for satisfying (24)-(26). Condition (30) is a slight strengthening of the incentive compatibility constraint of the power system holding all chips and experiencing a positive production shock. *Inter alia*, this condition implies that

$$V_N^N \leq \frac{p^2 u\left(\bar{y}-\epsilon\right)+p\left(1-p\right) u\left(\bar{y}-\epsilon+K\right)+p\left(1-p\right) u\left(\bar{y}+\epsilon-K\right)+\left(1-p\right)^2 u\left(\bar{y}+\epsilon\right)}{1-\beta}.$$

That is, V_N^N is bounded above by the symmetric payoff that the players would achieve if they always transferred electricity in asymmetric production states. Finally, adapting arguments in Lemma 10 of Abdulkadiroglu and Bagwell (2012), it follows that $V_n^N \leq V_{n.}^{N+1}$ for every $n = 0, ..., N$. Given all this, it is possible to apply the algorithm of Abdulkadiroglu and Bagwell (2012) to find the **optimal K-capacity chip mechanism** satisfying (30):

- Start with $N = 1$: Given N-chips, write the expected payoffs recursively and calculate the unique solution of the resulting system of equations, (21)-(23).
- Check if (30) is violated. If it is violated, then the optimal number of chips is $N-1$; otherwise repeat the two steps with $N+1$ chips.

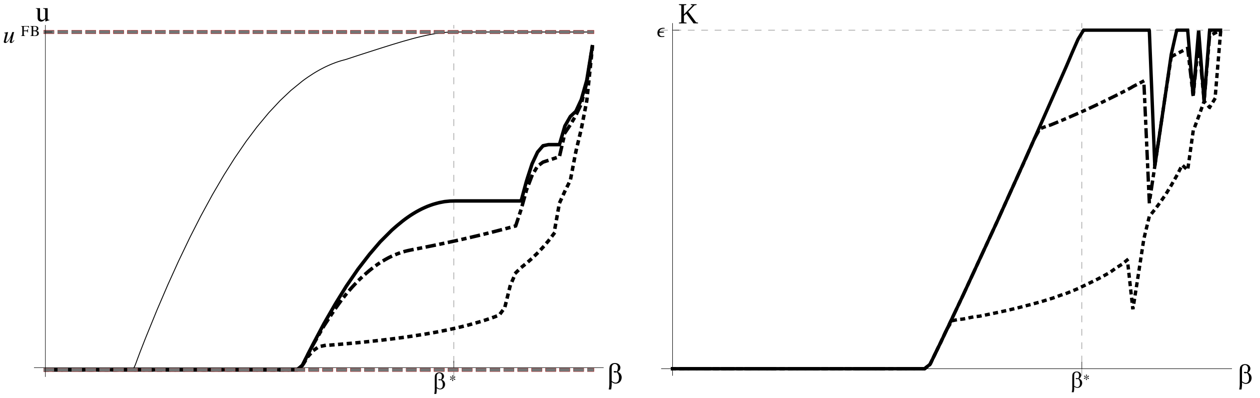
In the chip mechanism, the interconnection capacity can be endogenized in the same manner as described in Section 2: in the first stage, a social planner chooses the optimal interconnector's capacity K^* at increasing cost and in the second stage, the connected power systems introduce chips to establish the optimal incentive compatible K^*-capacity chip mechanism. The mechanism that results from this two-stage game will be referred to as the **optimal chip mechanism.**

Figure 2a illustrates the scope for thus found optimal chip mechanism to improve on autarky, based on the same model parameters as in section 3.3. The figure depicts the per-period expected payoff of a power system participating in the optimal chip mechanism net of interconnection costs. The bottom dotted line corresponds to expected per-period utility in autarky; the top dotted line corresponds to the symmetric first-best per-period utility. The payoff is expressed in per-period terms through multiplying the corresponding life-time utility by $(1-\beta)$. The vertical line at β^* is added for the reference: At $\beta = \beta^*$, the first best contract is enforceable when production shocks are observable and interconnection cost is zero. The optimal chip mechanism fails to achieve the first best welfare when $\beta = \beta^*$ even in the absence of the interconnection cost (the thick solid line representing the per-period utility in the optimal chip mechanism with zero interconnection costs is well below the top dashed line). For comparison purposes, in Figure 2a a thin black line depicts the expected per-period utility of a power system participating in an optimal sustainable contract with *observable production* shocks and no interconnection costs. The comparison of expected utilities with observable and unobservable production shocks (that is, the comparison of the thick and the thin black lines in Figure 2a) makes it clear that establishing an independent system operator capable of monitoring production shocks in the connected power systems brings much higher welfare gains than a simple chip mechanism considered in this section.

Every time the per-period expected payoff of a power system makes a (smooth) step, the optimal number of chips is incremented by one. Thus, the figure demonstrates that as β increases, the number of chips consistent with incentive compatibility increases, thereby increasing the welfare benefit of the mechanism.

Figure 2b demonstrates that the optimal transmission capacity K^* that maximizes long-run welfare in the chip mechanism is non-monotone in β. In particular, incrementing the optimal number of chips goes hand-in-hand with a reduction in the optimal interconnection capacity. Reducing K relaxes the only binding constraint (30), which allows adding an extra chip at lower β than would have been possible if K remained fixed. From welfare perspective, adding more chips is more valuable than having extensive transmission capacity, because electricity transfers are partially suspended whenever one power system holds all the chips and thus the installed capacity has higher probability of remaining idle in a mechanism with fewer chips.

The chip mechanism considered here effectively is a flexible electricity swap agreement that breaks even on average (i.e. where power flows between the parties to the agreement are balanced in the long-run). A more sophisticated chip mechanism could feature more flexible use of volumes or price adjustments. For example, it could feature changing terms of trade whenever a power system becomes constrained, so that each additional MWh of electricity provided by the constrained power system commands a higher price in terms



(a) The per-period expected payoff of a power system participating in the optimal chip mechanism net of interconnection costs.

(b) The optimal interconnection capacity: The top dotted line corresponds to the maximal electricity transfer ϵ.

Figure 2: The per-period expected payoff and interconnection capacity in the optimal contract as a function of discount factor β, when $\bar{y} = 100$, $\epsilon = 15$, $p = 0.2$ and interconnection costs are of the form $c(K) = aK^2$. In both figures, the thick solid line corresponds the optimal chip mechanism when interconnection is costless; the dash-dotted line corresponds to the optimal chip mechanism with $c(K) = 0.0002K^2$; the dotted line corresponds to the optimal chip mechanism with $c(K) = 0.002K^2$.

of future electricity transfers. This could induce power systems to provide more electricity export than in the case where the exchange rate between a MWh today and MWh in future is always one.

5 Conclusions

This paper proposes a theoretical framework for analyzing the scope for voluntary electricity sharing arrangements among power systems where functioning contract enforcement institutions do not exist and are difficult to establish. Drawing from the game-theoretic literature, we adapt the efficient risk sharing model with limited commitment to electricity sharing arrangements, where each power system can terminate ongoing cooperation at any moment. The paper's main insight is that a voluntary electricity sharing arrangement is capable of bringing welfare gains when electricity production shocks are perfectly observable by an independent system operator as well as when production shocks are only privately observable by each connected power system. As the realized gains from electricity trading arrangements are higher when electricity production shocks are publicly observable, this study argues for establishing cross-regional independent system operator in countries contemplating electricity trading arrangements. This conclusion is particularly important as majority of international development projects in developing country electricity sector overwhelmingly focus on investment in power plants and transmission lines, while human and institutional failures could matter as much as physical constraints.

Our theoretical results indicate that for successful cross-border cooperation, the predetermined risk of terminating an ongoing relationship should be sufficiently small. Hence, a meaningful quantitative evaluation of the scope for electricity sharing requires an estimate of this risk. In practice, the risk of termination may stem from, e.g., political economy issues in one or both countries that host the interconnector, but further research is required to analyze carefully the determinants and magnitude of this risk in specific regions of interest.

Introducing this theoretical framework to a new, highly idiosyncratic, electricity sector requires us to explicitly model investment in new transmission lines, thereby endogenizing the transmission capacity. In the real world, power systems, which have not been previously involved in cross-border electricity exchange, are unlikely to have extensive transmission lines across borders. In most developing countries, transmission constraints are a serious setback to electricity trading, as the existing transmission capacity is insufficient for clearing most of the requested cross-border trades. Our theoretical results demonstrate that investment in new interconnectors is socially desirable when sustainable electricity trading arrangements are feasible. However, high costs of interconnection may result in a significant decline in the long-term welfare under the optimal electricity trading contract.

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