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Contracting for the Second Best in Dysfunctional Electricity Markets

Arina Nikandrova
Jevgenijs Steinbuks

The World Bank
Development Research Group
Environment and Energy Team
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Abstract

Power pools constitute a set of sometimes complex institutional arrangements for efficiency-enhancing coordination among power systems. Where such institutional arrangements do not exist, there still can be scope for voluntary electricity-sharing agreements among power systems. This paper uses a particular type of efficient risk-sharing model with limited commitment to 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 fluctuations in connected power systems, establishing quasi-markets for trading excess electricity through the kind of mechanism described here helps achieve sustainable cooperation in mutually beneficial electricity sharing.

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Contracting for the Second Best in Dysfunctional Electricity Markets*

Arina Nikandrova and Jevgenijs Steinbuks

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*Nikandrova: Birkbeck, University of London, a.nikandrova@bbk.ac.uk. Steinbuks: Development Research Group, The World Bank, jsteinbuks@worldbank.org. Acknowledgements: We would like to thank Javier Bustos Salvagno, Avinash Dixit, Romans Pancs, Vladimir Parail, Michael Pollitt, Michael Toman, and the participants of the 12th Annual International Industrial Organization Conference for their helpful suggestions and comments. Responsibility for the content of the paper is the authors' alone and does not necessarily reflect the views of their institutions, or member countries of the World Bank. Financial support from the Australian Agency for International Development and from the Partnership for South Asia Regional Integration Programmatic Trust Fund is greatly acknowledged.

1 Introduction

Availability of modern electric power infrastructure is widely recognized as one of the key driving forces for accelerated economic development (Jorgenson 1984, Toman and Jemelkova 2003, Briceno-Garmendia et al. 2004, Chakravorty et al. 2014). Yet in many developing countries, the electric power systems are dysfunctional, characterized by poor access to electric grid, unreliable power supply, inefficient generating capacities, deficient maintenance, and losses in transmission and distribution (Eberhard et al. 2008, Foster and Steinbuks 2009, Sen and Jamasb 2012). Seeking to improve the performance of their electric power systems, many developing countries have undertaken deregulation, privatization, and interconnection processes, with the final goal of creating functioning wholesale and retail electricity markets (Joskow 2008). While these reforms have led to positive and globally widespread, though modest, efficiency gains (Pollitt 2012b), the reform process in most developing countries has appeared to be slow and difficult, even after more than two decades of reforms (Besant-Jones 2006, Kessides 2012). In light of the unique institutional characteristics of many developing countries, increasing doubts have been recently expressed about the applicability of the standard textbook model of utility reform to these countries. In many parts of the world, electricity markets have evolved or are evolving into hybrid forms, adapting some elements of the standard market-based model, but not completely unbundled, privatized, or competitive (Gratwick and Eberhard 2008).

The integration of electricity markets is frequently seen as a low-hanging fruit of improving the performance of electric power systems. A number of regions, including Northern Europe, regions in the United States, Western and Southern Africa, and Latin America moved in the direction of integrating their electricity systems (Ochoa et al. 2013). 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. The empirical evidence indicates that regional integration of electricity markets has been largely successful in developed countries, such as North European countries (Nord Pool) or Pennsylvania-New Jersey-Maryland (PJM) interconnection in the United States (Douglas 2006, Pollitt 2008), but less so in some developing countries, e.g., in West Africa and Central America, where despite significant potential benefits traded quantities are still extremely small (Eberhard et al. 2008, Pineau 2008, Reinstein et al. 2011).

One explanation for poor performance of regionally integrated electric systems in the developing countries is that weak institutional arrangements are not capable of enforcing "contracts" among member states.[1] In developed countries electricity trading is facilitated and enforced through complex institutional mechanisms. These arrangements frequently feature an independent system 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 2012a). 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 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). These bilateral electricity trading contracts are often subject to a "hold-up" problem (Williamson 1979, Tirole 1986), whereby large sunk costs of establishing electricity trading arrangements create incentives for not honoring the terms of the contract by either of the trading sides.

[1] 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.

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 with limited commitment to electricity sharing arrangements. The model has been developed theoretically, among others, by Thomas and Worrall (1988), 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 are connected via an electricity interconnector. 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 capacity and the electricity supply is perfectly inelastic. Furthermore, electricity 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.[2]

The model's main insight is that the scope for cooperation 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. These risks are not trivial in many developing countries. For example, it is widely documented that 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). If the 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 still yields an improvement over autarkic outcome as it allows some intertemporal smoothing of electricity consumption. If the expected probability of terminating an ongoing relationship is high (e.g., in cases of very substantial political risks), 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-

[2]This assumption is made for computational convenience, but results would be qualitatively the same with less severe, but more realistic punishments (see footnote 11 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.[3]

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 market 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

[3]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.

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.

2 Model

Consider a version of a dynamic risk sharing model with limited commitment introduced by Kocherlakota (1996). Two power systems, or players 1 and 2, are connected via an electricity interconnector with exogenous capacity K. Both systems have identical marginal costs of generation, which are normalized to zero.[4] 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.[5] Thus, at time t, the domestic electricity production in 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

[4]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.

[5]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 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.

symmetric around zero and has a discrete support

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

where $\epsilon^s < \epsilon^{s+1}$ and $\bar{y} + \epsilon^1 \geq 0$. Shocks $\epsilon_{i,t}$ are i.i.d. across time with $p^s := \mathbb{P}\left(\epsilon_{i,t} = \epsilon^s\right)$. 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. 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.[6]

Example 1. *Independent production shocks:* If $\pi^{s,s'} = p^s p^{s'}$, the production shocks are independent across the power systems and aggregate production varies over time.

Alternatively, the production shocks could be perfectly negatively correlated.[7]

Example 2. *No aggregate uncertainty:* If player 1 produces $y_{1,t}$, and player 2 produces $Y - y_{1,t}$, there is no aggregate uncertainty, but the distribution of output varies over time. As aggregate production is Y in every period, $y_i^s = Y - y_i^{S-s+1}$, where $y_i^s := \bar{y} + \epsilon^s$ and $y_i^{S-s+1} := \bar{y} + \epsilon^{S-s+1}$ is production of player i experiencing production shock ϵ^s and ϵ^{S-s+1}, respectively. Consequently, $p^s = p^{S-s+1}$ and $\pi^{s,s'} = p^s$ whenever $s' = S - s + 1$ and $\pi^{s,s'} = 0$ otherwise.

Power system i has the instantaneous utility function $u_i(c)$, which is increasing, strictly concave and continuously differentiable in domestic electricity consumption with $\lim_{c \to 0} u_i'(c) = +\infty$.[8]

[6] 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.

[7] See Ljungqvist and Sargent (2004), for a textbook treatment of this example.

[8] In addition, it is possible to normalize the utility function so that $u_i(\bar{y}) = 0$, $u_i(c) < 0$ for all $c < \bar{y}$

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

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

where $\delta \in (0,1)$ is a discount factor and $\mathbb{E}_t[\cdot]$ is expectation operator conditional on information publicly available at t. The discount factor δ can be viewed as 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. Alternatively, δ can also be viewed as being implied by the interest rate used to discount investment in the connected power systems. In either case, the magnitude of δ crucially depends on the frequency of interaction, with more frequent electricity exchange commanding higher δ.

We consider two alternative information structures. 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 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;[9] the transfer results

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 countries hardly produce enough electricity to prevent involuntary interruption of demand.

[9] Assuming that one player makes a transfer, while the other player makes no transfer is without loss of

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 $(c_1(h^t), c_2(h^t))$, where $c_i(h^t)$ 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, $c_{i,t} = c_i(h^t)$. 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.

3 Two Benchmarks

3.1 Autarky Outcome

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

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

to player i.

Payoff $\underline{v}_i$ defines the reservation utility of power system i in any voluntary contract. The assumption of concave instantaneous utility functions implies that non-trivial contracts with strictly positive electricity transfers may yield higher lifetime utility to each power system whenever they enable electricity consumption smoothing over time as well as over states.

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.

3.2 The First-Best Efficient Allocation

Now consider a planner who 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.[10] The **first-best efficient contract** is a solution to the following optimization problem:

$$\max_{\{c_{1,t},c_{2,t}\}_{t=0}^{\infty}} \mathbb{E}_0 \left[\sum_{t=0}^{\infty} \delta^t \left(u_1 \left(c_{1,t} \right) + \lambda_0 u_2 \left(c_{2,t} \right) \right) \right]$$

$$\text{s.t.} \sum_{i=1}^{2} c_{i,t} \leq Y_t \quad \forall i, t \geq 0 \tag{2}$$

$$y_{i,t} - K \leq c_{i,t} \leq y_{i,t} + K \quad \forall i, t \geq 0 \tag{3}$$

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \delta^t u_i \left(c_{i,t} \right) \geq \underline{v}_i \qquad \forall i. \tag{4}$$

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 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, as risk-averse players 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 $\epsilon_{i,t}$

[10] 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.

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).

4 Optimal Self-Enforcing Contracts

The planer's problem 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, any arrangement 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. In particular, every time a power system is called upon to transfer electricity to a neighboring power system, it weighs the cost of fulfilling this obligation against the benefit from future cooperation. The electricity sharing contract is voluntary or self-enforcing if after any history of production shocks, the discounted present value of the contract's future benefit flow outweighs the current (welfare) cost of export. This section demonstrates that the history-by-history participation constraints limit the scope for cooperation among the power systems.

It will be assumed 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 rate δ. 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.[11]

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.

4.1 Cooperative Outcomes with Perfectly Observable Shocks

We first 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.[12]

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

[11] 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).

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

2. Then the conditional Pareto frontier satisfies the following Bellman equation:

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

subject to

$$\lambda: \qquad u_2(c) + \delta \sum_{s=1}^{S}\sum_{s'=1}^{S} \pi^{s,s'} U^{s,s'} \geq U \tag{8}$$

$$\delta\pi^{s,s'}\eta_1^{s,s'}: \qquad V^{s,s'}\left(U^{s,s'}\right) \geq u_1\left(y_1^{s,s'}\right) + \delta \underline{v}_1 \ \forall (s,s') \tag{9}$$

$$\delta\pi^{s,s'}\eta_2^{s,s'}: \qquad U^{s,s'} \geq u_2\left(y_2^{s,s'}\right) + \delta \underline{v}_2 \ \forall (s,s') \tag{10}$$

$$\underline{\mu}: \qquad c \geq y_2^{\hat{s},\hat{s}'} - K \tag{11}$$

$$\bar{\mu}: \qquad c \leq y_2^{\hat{s},\hat{s}'} + K \tag{12}$$

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 (8) 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 (9) and (10) 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 (11) and (12) 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 is a concave problem for which the first-order conditions are necessary and sufficient.[13] In particular, by taking a convex combination of two sustainable contracts, 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

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

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 $\underline{V}^{\hat{s},\hat{s}'} = u_1\left(y_1^{\hat{s},\hat{s}'}\right) + \delta \underline{v}_1$ and $\underline{U}^{\hat{s},\hat{s}'} = u_2\left(y_2^{\hat{s},\hat{s}'}\right) + \delta \underline{v}_2$. Furthermore, the fact the total production in every period 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:

$$\frac{u_1'\left(Y^{\hat{s},\hat{s}'} - c\right)}{u_2'(c)} = \lambda + \frac{\underline{\mu} - \bar{\mu}}{u_2'(c)} \tag{13}$$

$$\frac{\mathrm{d}V^{s,s'}}{\mathrm{d}U^{s,s'}} = -\frac{\lambda + \eta_2^{s,s'}}{1 + \eta_1^{s,s'}} \tag{14}$$

$$\frac{\mathrm{d}V^{\hat{s},\hat{s}'}}{\mathrm{d}U} = -\lambda. \tag{15}$$

According to the envelope condition (15), 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 (14). The current consumption profile of players is pinned down by equation (13), 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 $\lambda(h^t)$ be the value of λ at date t after the history h^t. Ligon et al. (2002) shows that $\lambda(h^t)$ 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 $\lambda(h^t)$ evolves according to* *the following rule. Let h^t be period-t history and let $\left(\epsilon^s, \epsilon^{s'}\right)$ be the state in period $t+1$, then*

$$\lambda\left(h^{t+1}\right) = \begin{cases} \underline{\lambda}^{s,s'} & \text{if } \lambda\left(h^t\right) < \underline{\lambda}^{s,s'} \\ \lambda\left(h^t\right) & \text{if } \lambda\left(h^t\right) \in \left[\underline{\lambda}^{s,s'}, \bar{\lambda}^{s,s'}\right], \\ \bar{\lambda}^{s,s'} & \text{if } \lambda\left(h^t\right) > \bar{\lambda}^{s,s'} \end{cases} \tag{16}$$

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 (13) 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, (14) 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. In fact, for every state $\left(\epsilon^s, \epsilon^{s'}\right)$, there is an interval of possible relative Pareto weights $\left[\underline{\lambda}^{s,s'}, \bar{\lambda}^{s,s'}\right]$. If previous period relative Pareto weight lies outside the current interval, λ must be changed by the smallest possible amount to get it into the new interval. In the updating rule (16), weight $\underline{\lambda}^{s,s'}$ corresponds to player 2 being held down to its minimum surplus $u_2\left(y_2^{s,s'}\right) + \delta \underline{v}_2$ and being constrained; weight $\bar{\lambda}^{s,s'}$ corresponds to player 1 being held down to its minimum surplus $u_1\left(y_1^{s,s'}\right) + \delta \underline{v}_1$ and being constrained.

The time variation of λ ensures that the power system with the binding participation constraint is promised a higher future electricity consumption stream. The increase in the expected future consumption is just sufficient to prevent the default of the constrained player. Moreover, the resulting higher expected consumption level will remain unchanged as long as there are no binding participation constraints. Thus in the optimal contract, a power system is induced not to abandon the electricity sharing contract by increasing its future expected consumption of electricity permanently, not only in the period where the power system is tempted to default.

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

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

(ii) It is clear that when $\delta = 0$, the only sustainable contract is autarkic. Proposition 2 (v) in Ligon et al. (2002) shows that also for a sufficiently small, but strictly positive δ, 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 $\bar{\delta} > \delta > \underline{\delta}$ 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 (16) 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 δ. Thus also the electricity transfers are continuous in δ, leading to a continuous welfare improvement. □

When $\delta \geq \bar{\delta}$, some first-best contract is sustainable. By (13), in a first-best contract, the ratio of the marginal utilities of power systems varies only insofar as the capacity constraint of the interconnector is binding. Hence, to satisfy (16) it must be the case that all λ intervals characterizing the optimal contract have some points in common. If λ_0 belongs to the overlap region, λ never changes. Moreover, starting from any λ_0, the updating rule (16) leads λ towards the region where the λ intervals overlap and any contract converges to some first-best contract in the long-run.

When $\delta \leq \underline{\delta}$, the future benefit from continuing cooperation is heavily discounted and as such is smaller that the immediate benefit from reneging on the required electricity transfer. Consequently, no transfers are ever made and autarky is the only sustainable outcome. In this case, each λ interval is degenerate and contains only the associated autarkic ratio of marginal utilities.

For intermediate $\delta \in \left(\underline{\delta}, \bar{\delta}\right)$, λ intervals are non-degenerate and power systems make electricity transfers to each other. These transfers achieve some consumption smoothing and thus are welfare improving. However, attaining full consumption smoothing is not possible as transfers are limited by the binding participation constraints. To induce higher transfers, whenever the exporting power system's participation constraint binds, this power system is promised a higher consumption stream in the future, i.e., $\lambda \neq \lambda_0$. As δ increases, participation constraints in more states get relaxed and more extensive consumption smoothing becomes feasible.

Note that by the Envelope theorem

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

where inequality is strict when either constraint (11) or constraint (12) binds. Thus, the model implies that the social surplus generated by an optimal sustainable contract is strictly increasing in K, the interconnector's capacity, only when interconnector's capacity constraint binds in some state. On its own this observation is trivial, but whether the interconnector's capacity constraint is sometimes biding in an optimal contract depends on the discount factor δ. In particular, as discussed above, for low values of δ, the binding participation constraints of power systems limit the optimal sustainable electricity transfers, but as δ increases, the participation constraints get relaxed and optimal electricity transfers increase. Consequently, the threshold capacity at which the interconnector's capacity constraint ceases to bind in any state also increases with δ. This suggests that in a model where in the first stage, a social planner chooses the interconnector's capacity (at some increasing cost) and in the second stage, the connected power systems engage in a sustainable electricity sharing arrangement, the optimal interconnector's capacity would be increasing in δ. 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.

Examples

To illustrate some properties of the model we consider two simple examples constructed along the lines of Examples 1-2 in Section 2.[14] In the first example, production shocks of the two power systems are perfectly negatively correlated and there is no aggregate uncertainty; in the second example, power systems are subject to independent production shocks. In both examples, it is assumed 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.

No aggregate uncertainty

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

[14] Both examples are very close to the example in Ligon et al. (2002).

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

$$\frac{u(\bar{y})}{1-\delta} \geq u(\bar{y}+\epsilon) + \delta \underline{v}, \tag{17}$$

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

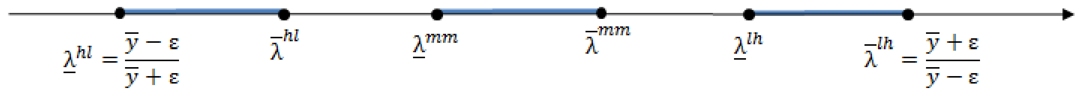
In terms of characterization of the optimal contract described in Proposition 1, there is an interval of relative Pareto weights λ corresponding to each state hl, lh and mm. Proof of Proposition 2 implies that with logarithmic utility $\underline{\lambda}^{hl} = (\bar{y}-\epsilon)/(\bar{y}+\epsilon)$ and $\bar{\lambda}^{lh} = (\bar{y}+\epsilon)/(\bar{y}-\epsilon)$. Moreover, since the setup is symmetric, it must be the case that $\bar{\lambda}^{hl} = 1/\underline{\lambda}^{lh}$ 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 (see Figure 1). In each of these cases, (16) determines the evolution of λ.[15]

Participation constraint (17) defines a critical discount factor $\bar{\delta}$ such that for all $\delta \geq \bar{\delta}$, 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.[16]

By proposition 2, when $\delta \leq \underline{\delta}$, no non-autarkic contract is sustainable. Hence, in each state

[15] 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 (13) 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.

[16] 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 $\delta = \bar{\delta}$, the equal-payoff contract is the only sustainable first-best efficient contract. The set of sustainable first-best efficient electricity sharing arrangements expands as δ increases.



(a) When δ is relatively low, the λ intervals are disjoint.

(b) For higher values of δ, the λ intervals are partially overlapping.

Figure 1: **The λ intervals:** When δ is very low, the λ interval for each state is degenerate and contains a single value equal to the autarkic ratio of marginal utilities in that state. As δ increases, the intervals begin to expand in a continuous fashion and are initially disjoint (1a). For relatively high δ, intervals partially overlap (1b). Eventually, for $\delta \geq \bar{\delta}$ all three intervals have some points in common, which implies that some first-best efficient contracts are sustainable.

each power system consumes what it produces.

In the intermediate range of δ, the optimal contract is a compromise between the first-best and the autarkic contract. To see this suppose that $\underline{\delta} < \delta < \bar{\delta}$ 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'.

For concreteness, suppose that δ is relatively low so that the λ intervals are disjoint, but non-degenerate. Suppose that power system 2 is the first to receive a bad shock, i.e., state hl is realized. Then, λ falls to $\bar{\lambda}^{hl} < \lambda_0 = 1$ and power system 1 makes an electricity transfer to power system 2 so as to keep the ratio of marginal utilities $u_1'\left(Y^{\hat{s},\hat{s}'} - c\right)/u_2'(c)$ equal to the new relative Pareto weight $\bar{\lambda}^{hl}$. The transfer is such that power system 1 is just indifferent between continuing cooperation and abandoning the contract, i.e., the participation constraint of the power system 1 is binding and its expected life-time utility is $\underline{V}^{hl} \equiv u(\bar{y} + \epsilon) + \delta \underline{v}$. Because of the binding participation constraint of power system 1, the electricity transfer to power system 2 is lower than ϵ and does not provide full insurance. Suppose that in the next period, state mm is realized, so that the electricity productions of the two power systems are equal again. Now λ increases to $\underline{\lambda}^{mm}$, but does not reach $\lambda_0 = 1$. Thus, now, unlike the initial periods, in state mm power system 2 makes a transfer to power system 1. This transfer makes power system 2 indifferent between continuing cooperation and abandoning

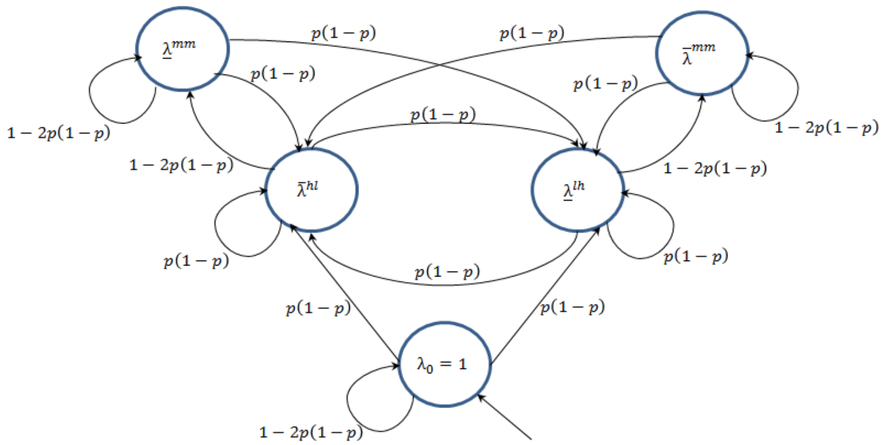


Figure 2: $\underline{\delta} < \delta < \bar{\delta}$: The Markov chain describing the evolution of λ starting from the initial value λ_0, when the λ intervals are non-degenerate, but disjoint.

the contract, i.e., now participation constraint of power system 2 is binding and power system 2 expects life-time utility of $\underline{U}^{mm} \equiv u(\bar{y}) + \delta \underline{v}$. By making electricity transfers in a state with symmetric electricity production power system 2 'repays' the transfer obtained previously in state hl. The repayment continues until state lh is realized, upon which the roles of the power systems switch. In particular, in state lh, power system 2 is helping out power system 1 and power system 1 becomes a new 'debtor', who will be required to make transfers in state mm. The credit that power system 1 has previously extended to power system 2 is forgotten and for the future electricity transfers, all that matters is which power system was last to receive a bad shock, i.e., the optimal electricity sharing arrangement displays amnesia.[17]

Note that after the first realization of a state with asymmetric production profile, λ only takes four different values, $\bar{\lambda}^{hl}$, $\underline{\lambda}^{mm}$, $\bar{\lambda}^{mm}$ and $\underline{\lambda}^{lh}$. This implies that in each period, also each player's consumption of electricity and expected continuation utility can take only four values and the consumption allocation converges weakly to the stationary distribution. Moreover, since the λ intervals are time independent and since the transition probabilities are determined by the stochastic process governing the production shocks, the consumption allocation converges to the same long-run distribution independently of the initial relative Pareto weight λ_0.

The case with partially overlapping λ intervals is very similar to the case of disjoint intervals,

[17]The term "amnesia" of consumption was first coined by(Kocherlakota 1996).

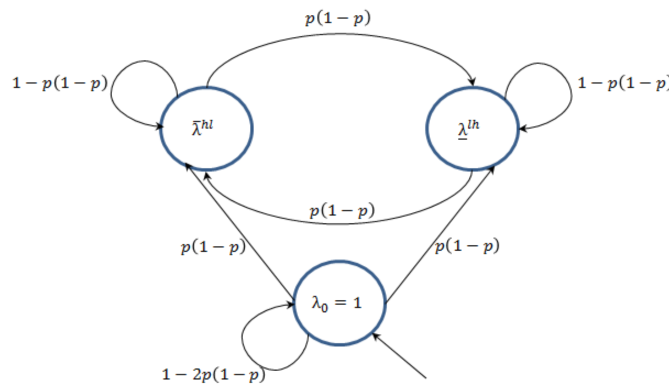


Figure 3: $\underline{\delta} < \delta < \bar{\delta}$: The Markov chain describing the evolution of λ starting from the initial value λ_0, when the λ intervals are partially overlapping.

only now more electricity sharing is sustainable. Since $\bar{\lambda}^{hl} \geq \underline{\lambda}^{mm}$ and $\bar{\lambda}^{mm} \geq \underline{\lambda}^{lh}$, now, given the current assignment of roles (borrower or lender), it is possible to keep the ratio of marginal utilities the same in the borrowing state (hl for player 2 and lh for player 1) and the repayment state mm without violating the participation constraint of the current borrower in state mm. However, the assignment of roles still depends on which power system was the last to experience the bad shock. This is because in states with asymmetric production, the participation constraint of the power system that makes a transfer is still binding. In the long-run λ only takes two different values $\bar{\lambda}^{hl}$ and $\underline{\lambda}^{lh}$ and thus the support of the unique stationary distribution of the expected life-time utilities also contains only two points (see Figure 3).

Figure 4 illustrates the scope for the optimal contract to improve on autarky, when $\bar{y} = 100$, $\epsilon = 15$ and $p = 0.2$. In particular, the calculations underlying the figure show that for $\delta \leq 0.914$, the λ intervals are degenerate and only autarkic outcome is sustainable, while for $\delta \geq 0.975$, all three λ intervals have points in common and the first-best symmetric payoff is sustainable. For $\delta \in (0.914, 0.975)$, the optimal contract improves on autarky, but is not first-best efficient. In particular, for $\delta \in (0.914, 0.955)$, the λ intervals have non-empty interiors, but are disjoint and for $\delta \in [0.955, 0.975)$, 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.

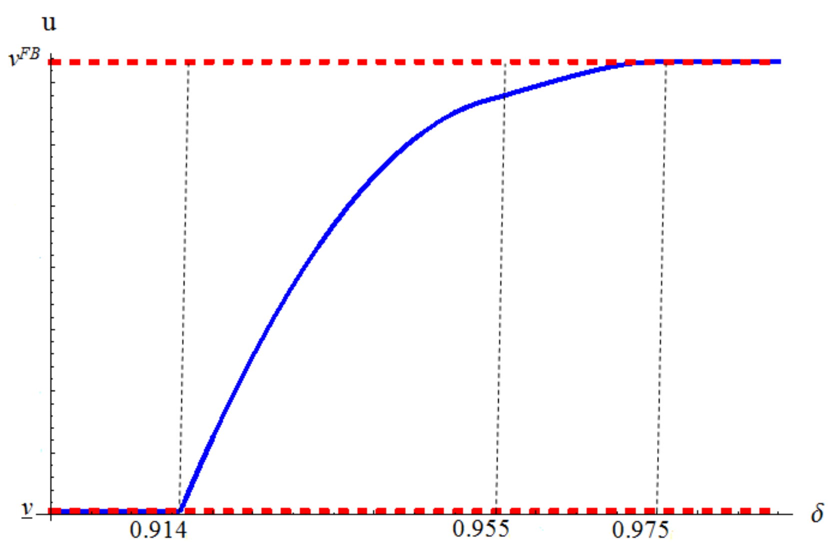


Figure 4: The per-period expected payoff of a power system participating in the optimal contract, when $\bar{y} = 100$, $\epsilon = 15$ and $p = 0.2$. The bottom red dotted line corresponds to expected per-period utility in autarky; the top red dotted line corresponds to $u(\bar{y})$, the symmetric first-best per-period utility; the blue solid line corresponds to the per-period expected payoff in the optimal contract with $\lambda_0 = 1$. All utilities are expressed in per-period terms through multiplying the corresponding life-time utility by $(1 - \delta)$.

Independent shocks

Suppose that production shocks are independent across the power systems and across time and can take two values $\{-\epsilon, \epsilon\}$ with $\mathbb{P}(\epsilon_t = -\epsilon) = p$. There are then four states, labeled hh, hl, lh and ll, where hh indicates that both power systems produce $\bar{y} + \epsilon$, hl indicates that player 1 produces $\bar{y} + \epsilon$, while player 2 produces $\bar{y} - \epsilon$, and so on. In this example the aggregate production of electricity varies across states. Nevertheless, the formal analysis is almost identical to the example with perfectly negatively correlated production shocks. This is because with logarithmic utility, the λ intervals for the states ll and hh coincide and by symmetry there are again just three cases to consider: (1) λ intervals are disjoint; (2) intervals partially overlap; and (3) all λ intervals have some points in common.[18] Given the parametrization, Figures 1, 3 and 2 are also applicable to this example, if interval $\left(\underline{\lambda}^{mm}, \bar{\lambda}^{mm}\right)$ is understood to apply in states hh and ll.

As before, also in this example, in a state with asymmetric production distribution, the disadvantaged power system receives an electricity transfer and becomes a debtor. The current debtor repays the debt in states with symmetric production distribution, but now the repayments are scaled up or down, proportionately to the changes in aggregate electricity production.

4.2 Cooperative Outcomes with Privately Observable Shocks

In Section 4 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 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.

[18] See Ligon et al. (2002) for details.

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.[19]

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 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.

[19] Under perfect monitoring of shocks, a negative production shock also results in a reduction of current and future electricity consumption, when discount factor δ 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.

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.[20]

By the way of illustration, consider the example in Section 4.1 with independent shocks taking two values $-\epsilon$ and $+\epsilon$. In this context, suppose that each player is privately informed of the realization of its current production shock and the 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.

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 $n = 1, ..., N-1$

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

and at the boundary

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

[20]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.

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

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 positive production shock to report its production truthfully, the mechanism must satisfy the following incentive compatibility constraints: for $n = 1, ..., N-1$

$$\begin{aligned} p\left(u\left(\bar{y}+\epsilon-K\right)+\delta V_{n+1}^N\right) &+ (1-p)\left(u\left(\bar{y}+\epsilon\right)+\delta V_n^N\right) \\ \geq p\left(u\left(\bar{y}+\epsilon\right)+\delta V_n^N\right) &+ (1-p)\left(u\left(\bar{y}+\epsilon+K\right)+\delta V_{n-1}^N\right) \end{aligned} \tag{18}$$

and at the boundary

$$p\left(u\left(\bar{y}+\epsilon-K\right)+\delta V_1^N\right)+(1-p)\left(u\left(\bar{y}+\epsilon\right)+\delta V_0^N\right) \geq u\left(\bar{y}+\epsilon\right)+\delta V_0^N \tag{19}$$

$$p\left(u\left(\bar{y}+\epsilon\right)+\delta V_N^N\right)+(1-p)\left(u\left(\bar{y}+\epsilon+K\right)+\delta V_{N-1}^N\right) \leq u\left(\bar{y}+\epsilon\right)+\delta V_N^N. \tag{20}$$

The constraint (19) 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 (20) 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 (18) 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. A chip mechanism satisfying constraints (18)-(20) is called *incentive compatible.*

Proposition 3 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 δ 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 δ, a K-capacity chip mechanism also fails to adjust the magnitude of the required electricity transfers in an optimal manner.

Proposition 3. *There exists a critical* $0 < \delta^* < 1$ *such that for all* $\delta \in (\delta^*, 1)$, *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.[21] In this mechanism, the only binding constraint is the incentive constraint of the player with no chips, (19), as this constraint implies (20) (by strict concavity of the utility function $u(\cdot)$) as well as the participation constraints of the power systems. Hence, by rearranging (19) it is possible to obtain a critical discount factor $\delta^* < 1$ such that for all $\delta \geq \delta^*$ the one-chip K-capacity mechanism is incentive compatible. This 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 4.1. If $\underline{\delta} < \delta < \bar{\delta}$, 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 δ, any incentive compatible chip mechanism must yield lower life-time utility to players than the optimal contract. Suppose $\delta \geq \bar{\delta}$. For this range of δ, 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

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

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. □

Note that in an N-chip mechanism, condition

$$\delta \left[V_N^N - V_{N-1}^N \right] \geq u(\bar{y} + \epsilon) - u(\bar{y}) \tag{21}$$

is sufficient for incentive compatibility as it implies all the incentive compatibility as well as participation constraints of the power systems. Given this, it is possible to apply the algorithm of Abdulkadiroglu and Bagwell (2012) to find the best K-capacity chip mechanism satisfying (21):

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

Figure 5 illustrates the scope for thus found ϵ-capacity and $\epsilon/2$-capacity chip mechanisms to improve on autarky, when $\bar{y} = 100$, $\epsilon = 15$ and $p = 0.2$. The figure demonstrates that as δ increases, the number of chips consistent with incentive compatibility increases, thereby increasing the welfare benefit of the mechanism. Reducing K, the capacity of the chip mechanism, reduces its welfare gains for high δ, at the same time relaxing the binding incentive compatibility constraints for lower δ. Thus reducing K can increase the range of the discount factors for which some cooperation is feasible. This is consistent with findings in Section 4: in an optimal sustainable contract, electricity transfers in asymmetric production states are lower than ϵ when discount factor δ takes intermediate values. For comparison purposes, Figure 5 also depicts the per-period utility of a power system participating in an optimal sustainable contract. It is 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.

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

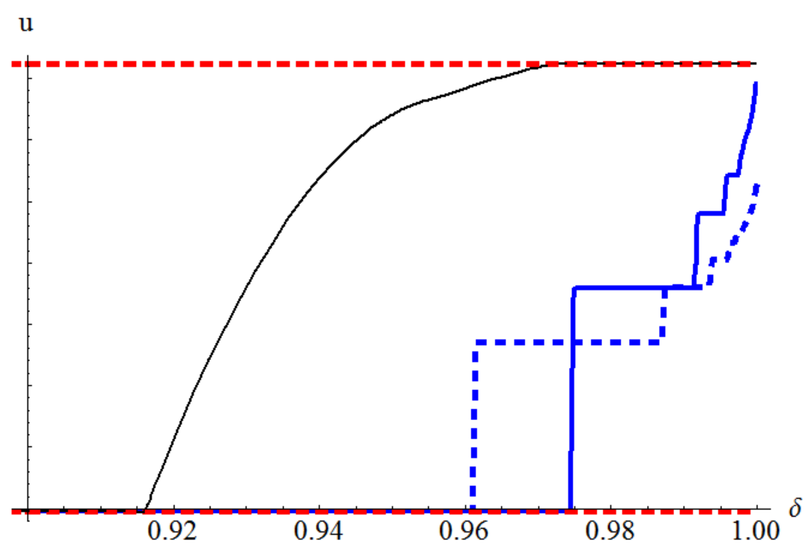


Figure 5: The per-period expected payoff of a power system when $\bar{y} = 100$, $\epsilon = 15$ and $p = 0.2$. The bottom red dotted line corresponds to expected per-period utility in autarky; the top red dotted line corresponds to the symmetric first-best per-period utility; the blue solid line corresponds to the per-period expected payoff in ϵ-capacity chip mechanism satisfying (21); the blue dashed line corresponds to the per-period expected payoff in $\epsilon/2$-capacity chip mechanism satisfying (21); the black solid line corresponds to the per-period expected payoff in the optimal contract with $\lambda_0 = 1$. All utilities are expressed in per-period terms through multiplying the corresponding life-time utility by $(1 - \delta)$.

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 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.

Introducing this theoretical framework to a new, highly idiosyncratic, electricity sector comes at a cost; in this early stage we have to assume that the transmission capacity is exogenous to derive key analytical results. 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. In future research we plan to explicitly model investment in new transmission lines, thereby endogenizing the transmission capacity. We also aim to account for the possibility that the transmission capacity is subject to failures due to unexpected physical damage or routine maintenance work on transmission lines.

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.

Another important dimension for further research is to deploy the theoretical framework to quantify feasible welfare gains from electricity exchange in regions contemplating cross-border cooperation, such as e.g., the South Asia region. In its current form, the model is well suited for studying asymmetric bilateral relationships. The analysis of multilateral pools will be qualitatively similar to that of bilateral contracts with participation and incentive compatibility constraints limiting the extent of cooperation. However, calibration and simulation of numerical models to fit actual grids and interconnector capacities in the regions of interest will be computationally more challenging because of extending the framework to power pools consisting of more than two parties, and using more complex functional forms for characterizing electricity supply and demand relationships.

References

Abdulkadiroglu, A.: 2013, Trust, Reciprocity, and Favors in Cooperative Relationships, *American Economic Journal: Microeconomics* **5**(2), 213–259.

Abdulkadiroglu, A. and Bagwell, K.: 2012, The Optimal Chips Mechanism in a Model of Favors, *Working paper*.

Abreu, D.: 1988, On the Theory of Infinitely Repeated Games with Discounting, *Econometrica* **56**(2), 383–96.

Albarran, P. and Attanasio, O. P.: 2003, Limited Commitment and Crowding out of Private Transfers: Evidence from a Randomised Experiment, *The Economic Journal* **113**(486), C77–C85.

Atkeson, A. and Lucas, R. E.: 1992, On Efficient Distribution with Private Information, *The Review of Economic Studies* **59**(3), 427–453.

Besant-Jones, J. E.: 2006, Reforming Power Markets in Developing Countries: What Have We Learned?, *Energy and Mining Sector Board Discussion Paper 19*, The World Bank.

Billette de Villemeur, E. and Pineau, P.-O.: 2010, Environmentally Damaging Electricity Trade, *Energy Policy* **38**(3), 1548–1558.

Billette de Villemeur, E. and Pineau, P.-O.: 2012, Regulation and Electricity Market Integration: When Trade Introduces Inefficiencies, *Energy Economics* **34**(2), 529–535.

Briceno-Garmendia, C., Estache, A. and Shafik, N.: 2004, Infrastructure Services in Developing Countries: Access, Quality, Costs and Policy Reform, *Policy Research Working Paper 3468*, The World Bank.

Chakravorty, U., Pelli, M. and March, B. U.: 2014, Intensive Margin of Electrification: Evidence from Rural India, *Journal of Economic Behavior and Organization,* **in press**.

Douglas, S.: 2006, Measuring Gains from Regional Dispatch: Coal-Fired Power Plant Utilization and Market Reforms, *The Energy Journal* **27**(1), 119–138.

Dubois, P., Jullien, B. and Magnac, T.: 2008, Formal and Informal Risk Sharing in LDCs: Theory and Empirical Evidence, *Econometrica* **76**(4), 679–725.

Eberhard, A., Foster, V., Briceno-Garmendia, C., Ouedraogo, F., Camos, D. and Shkaratan, M.: 2008, Underpowered: The State of the Power Sector in Sub-Saharan Africa, *Africa Infrastructure Country Diagnostic Background Paper 6*, The World Bank.

Farrell, J. and Maskin, E.: 1989, Renegotiation in Repeated Games, *Games and Economic Behavior* **1**(4), 327–360.

Federal Energy Regulatory Commission: 2004, Cost Ranges for the Development and Operation of a Day One Regional Transmission Organization, *Staff Report PL04-16-000.*

Fogelberg, S. and Lazarczyk, E.: 2014, Strategic Withholding through Production Failures, *IFN Working Paper 1015*, Research Institute of Industrial Economics.

Foster, A. D. and Rosenzweig, M. R.: 2001, Imperfect Commitment, Altruism, and the Family: Evidence from Transfer Behavior in Low-Income Rural Areas, *Review of Economics and Statistics* **83**(3), 389–407.

Foster, V. and Steinbuks, J.: 2009, Paying the Price for Unreliable Power Supplies : In-house Generation of Electricity by Firms in Africa, *Policy Research Working Paper 4913*, The World Bank.

Gately, D.: 1974, Sharing the Gains from Regional Cooperation: A Game Theoretic Application to Planning Investment in Electric Power, *International Economic Review* **15**(1), 195–208.

Gnansounou, E. and Dong, J.: 2004, Opportunity for Inter-regional Integration of Electricity Markets: the Case of Shandong and Shanghai in East China, *Energy Policy* **32**(15), 1737–1751.

Gratwick, K. N. and Eberhard, A.: 2008, Demise of the Standard Model for Power Sector Reform and the Emergence of Hybrid Power Markets, *Energy Policy* **36**(10), 3948–3960.

Hauser, C. and Hopenhayn, H.: 2008, Trading Favors: Optimal Exchange and Forgiveness, *Working paper*, Collegio Carlo Alberto.

Hertel, J.: 2004, Efficient and Sustainable Risk Sharing with Adverse Selection, *Working paper*, Princeton University.

Jorgenson, D. W.: 1984, The Role of Energy in Productivity Growth, *The Energy Journal* pp. 11–26.

Joseph, K. L.: 2010, The Politics of Power: Electricity Reform in India, *Energy Policy* **38**(1), 503–511.

Joskow, P.: 2008, Lessons Learned from Electricity Market Liberalization, *The Energy Journal* **29**(2), 9–42.

Kalla, S. J.: 2010, *Essays in Favor-trading*, PhD thesis, University of Pennsylvania.

Kessides, I. N.: 2012, The Impacts of Electricity Sector Reforms in Developing Countries, *The Electricity Journal* **25**(6), 79–88.

Kletzer, K. M. and Wright, B. D.: 2000, Sovereign Debt as Intertemporal Barter, *American Economic Review* **90**(3), 621–639.

Kocherlakota, N. R.: 1996, Implications of Efficient Risk Sharing without Commitment, *The Review of Economic Studies* **63**(4), 595–609.

Ligon, E., Thomas, J. P. and Worrall, T.: 2002, Informal Insurance Arrangements with Limited Commitment: Theory and Evidence from Village Economies, *The Review of Economic Studies* **69**(1), 209–244.

Ljungqvist, L. and Sargent, T. J.: 2004, *Recursive Macroeconomic Theory*, MIT Press.

Möbius, M.: 2001, Trading favors, *Unpublished manuscript*.

Mulder, M. and Schestalova, V.: 2006, Costs and Benefits of Vertical Separation of the Energy Distribution Industry: the Dutch Case, *Competition and Regulation in Network Industries* **7**, 197.

Musaba, L.: 2009, Energy Trading in the SAPP, Retrieved from `http://www.sapp.co.zw`.

Nayyar, S.: 2009, *Essays on Repeated Games*, PhD thesis, Princeton University.

Ochoa, C., Dyner, I. and Franco, C. J.: 2013, Simulating Power Integration in Latin America to Assess Challenges, Opportunities, and Threats, *Energy Policy* **61**, 267–273.

Olszewski, W. and Safronov, M.: 2012, Chip strategies in repeated games with incomplete information, *Working paper*, Department of Economics, Northwestern University.

Pierce, R., Trebilcock, M. and Thomas, E.: 2007, Regional Electricity Market Integration. A Comparative Perspective, *Competition and Regulation in Network Industries* **8**(2), 215–258.

Pineau, P.-O.: 2008, Electricity Sector Integration in West Africa, *Energy Policy* **36**(1), 210–223.

Pollitt, M.: 2008, The Arguments for and Against Ownership Unbundling of Energy Transmission Networks, *Energy Policy* **36**(2), 704–713.

Pollitt, M. G.: 2012a, Lessons from the History of Independent System Operators in the Energy Sector, *Energy Policy* **47**, 32–48.

Pollitt, M. G.: 2012b, The Role of Policy in Energy Transitions: Lessons from the Energy Liberalisation Era, *Energy Policy* **50**, 128–137.

Reinstein, D., Mateos, A., Brugman, A., Berman, L. and Johnson, T.: 2011, Regional Power Integration: Structural and Regulatory Challenges, *Energy Sector Management Assistance Program Report 58934 - LAC*, The World Bank.

Schechter, L.: 2007, Theft, Gift-giving, and Trustworthiness: Honesty is its Own Reward in Rural Paraguay, *The American Economic Review* **97**(5), 1560–1582.

Sen, A. and Jamasb, T.: 2012, Diversity in Unity: An Empirical Analysis of Electricity Deregulation in Indian States, *The Energy Journal* **33**(1), 83–130.

Sioshansi, F. P.: 2008, *Competitive Electricity Markets: Design, Implementation, Performance*, Elsevier.

Thomas, J. and Worrall, T.: 1988, Self-enforcing Wage Contracts, *The Review of Economic Studies* **55**(4), 541–554.

Thomas, J. and Worrall, T.: 1990, Income Fluctuation and Asymmetric Information: An Example of a Repeated Principal-Agent Problem, *Journal of Economic Theory* **51**(2), 367–90.

Tirole, J.: 1986, Procurement and Renegotiation, *The Journal of Political Economy* pp. 235–259.

Toman, M. A. and Jemelkova, B.: 2003, Energy and Economic Development: an Assessment of the State of Knowledge, *The Energy Journal* **24**(4), 93–112.

Williamson, O. E.: 1979, Transaction-Cost Economics: the Governance of Contractual Relations, *Journal of Law and Economics* pp. 233–261.