LONG-TERM POWER SYSTEMS INTEGRATION USING OSEMOSYS SAMBA - SOUTH AMERICA MODEL BASE - AND THE BARGAINING POWER OF COUNTRIES: A COOPERATIVE GAMES APPROACH

Gustavo Nikolaus Pinto de Moura

Tese de Doutorado apresentada ao Programa de Pós-graduação em Planejamento Energético, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Planejamento Energético.

Orientador: Luiz Fernando Loureiro Legey

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“A verdadeira sabedoria consiste em saber que você não sabe nada.”

“Eu não posso ensinar algo para alguém. Eu apenas posso fazê-lo pensar.”

Socrates

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INTEGRAÇÃO DE SISTEMAS ELÉTRICOS NO LONGO-PRAZO E O PODER DE BARGANHA DOS PAÍSES DA AMÉRICA DO SUL: UMA ABORDAGEM UTILIZANDO O MODELO OSEMOSYS SAMBA E OS JOGOS COOPERATIVOS

Gustavo Nikolaus Pinto de Moura

Março/2017

Orientador: Luiz Fernando Loureiro Legey

Programa: Planejamento Energético

Este trabalho pretende contribuir para uma melhor compreensão das vantagens e desvantagens da integração elétrica da América do Sul. Cenários de longo-prazo para o suprimento de eletricidade foram modelados no Open Source energy Modelling System – OSeMOSYS, baseados em dados disponíveis em relatórios nacionais e internacionais, utilizando uma nova estrutura de modelagem denominada South America Model Base – SAMBA. Aspectos relacionados a custos, emissões de carbono, reservatórios hidroelétricos, desempenho tecnológico, demanda de eletricidade, crescimento populacional, fusos horários e margem de reserva foram considerados. As perspectivas brasileira e boliviana do processo de integração foram modeladas a partir de dados apresentados em relatórios nacionais. A comparação de diferentes cenários permite estimar a contribuição da geração elétrica renovável e elucida as possibilidades de comércio internacional de eletricidade no longo-prazo. Adicionalmente, uma abordagem da teoria dos jogos cooperativos é utilizada para a identificação do poder de barganha de cada país no comércio internacional de eletricidade, por meio do cálculo do Valor de Shapley. A metodologia proposta poderá prover informações importantes aos formuladores de políticas e auxiliar a tomada de decisões durante negociações internacionais, reduzindo possíveis ações não-cooperativas.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

LONG-TERM POWER SYSTEMS INTEGRATION USING OSEMOSYS SAMBA - SOUTH AMERICA MODEL BASE - AND THE BARGAINING POWER OF COUNTRIES: A COOPERATIVE GAMES APPROACH

Gustavo Nikolaus Pinto de Moura

March/2017

Advisor: Luiz Fernando Loureiro Legey

Department: Energy Planning

This study intends to contribute to a better understanding of both advantages and drawbacks of power systems interconnection processes in South America. Based on data available in national and international reports, scenarios for the power supply sector expansion were modelled in the Open Source energy Modelling System – OSeMOSYS – using a new framework named South America Model Base – SAMBA. Features related to costs, carbon emissions, hydro reservoirs, technological performance, electricity demand, population growth, time zones and reserve margin were considered. The Brazilian and Bolivian perspectives of power systems integration were modelled according to data presented by national power plans. The comparison of different scenarios provides insights regarding the contribution of renewable energy generation and sheds light on cross-border trade perspectives in South America. Additionally, using a cooperative games approach, the bargaining power of each country (player) was calculated by applying the Shapley value concept. The proposed methodology may provide important information to support policy makers in international negotiations, thus considerably reducing incentives to non-cooperative actions.

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ATS – Alternative Trade SAMBA
CIER – Comisión de Integración Energética Regional
COP – Conference of the Parties
CSP – Concentrated Solar Power
EPE – Empresa de Pesquisa Energética
ETP – Energy Technologies Perspectives
ETSAP – Energy Technology Systems Analysis Program
GDP – Gross Domestic Product
GIS – Geographic Information System
IEA – International Energy Agency
IIRSA – Iniciativa para a Integração da Infraestrutura Regional Sul-Americana
MERCOSUL – Mercado Comum do Sul
NDC –Nationally Determined Contributions
ITS – Integration Trade SAMBA
LNG – Liquefied Natural Gas
NGCC – Natural Gas Combined Cycle
O&M – Operation and maintenance
OLADE – Organización Latino Americana de Energía
OPEC – Organization of the Petroleum Exporting Countries
OPTGEN - Generation and Interconnection Capacity Expansion Planning Model
OSeMOSYS – The Open Source energy Modelling System
PEI – Planejemento Energético Integrado
PV – Phtovoltaic Power Plant
RTS – Reference Trade SAMBA
SAMBA – South America Model Base
SIN – Sistema Interligado Nacional
UNASUR – Unión de Naciones Suramericanas
UNFCCC – United Nations Framework Convention on Climate Change
US EIA – United States Energy Information Administration
US EPA – United States Environmental Protection Agency
VPL – Valor Presente Líquido
WEO – World Energy Outlook

1. Introdução

Devido ao rápido crescimento da demanda de energia elétrica – com média anual de 3.7% entre 2005 e 2014 (CIER, 2015) –, os países da América do Sul têm acrescentado projetos internacionais em seus planos de investimento no setor elétrico. Por meio da formação de *joint-ventures*, são considerados projetos de usinas hidroelétricas e linhas de transmissão associadas. A expansão das interconexões elétricas internacionais pode proporcionar aumento da geração elétrica renovável com ganhos sinérgicos importantes oriundos da variabilidade sazonal das fontes renováveis e dos diferentes perfis de curvas de carga do continente. Ao se considerar todas as linhas de transmissão internacionais – associadas ou não a usinas hidroelétricas binacionais – existiam, em 2014, 18 interconexões internacionais em operação na América do Sul, conforme apresentado na Figura 1 e na Tabela 1 (CIER, 2015).

Figura 1 – Linhas de transmissão internacionais na América do Sul em 2014
Fonte: CIER (2015)

Tabela 1 - Linhas de transmissão internacionais na América do Sul em 2014
Fonte: Elaboração própria, baseado em CIER (2015)

Referência	Países	Capacidade Instalada (MW)	Status
1	Colômbia-Venezuela	150	Em operação
2	Colômbia-Venezuela	80	Em operação
3	Colômbia-Venezuela	150	Em operação
4	Colômbia-Panamá	300	Em estudo
5	Colômbia-Equador	250	Em operação
6	Colômbia-Equador	250	Em construção
7	Colômbia-Equador	113	Em operação
8	Equador-Perú	100	Em operação
9	Brasil-Venezuela	200	Em operação
10	Bolívia-Perú	150	Em estudo
11	Brasil-Paraguai	13100	Em operação
12	Brasil-Paraguai	50	Fora de operação
13	Argentina-Paraguai	30	Em operação
14	Argentina-Paraguai	90	Em operação
15	Argentina-Paraguai	3200	Em operação
16	Argentina-Brasil	2200	Em operação
17	Argentina-Brasil	50	Em operação
18	Argentina-Uruguai	1890	Em operação
19	Argentina-Uruguai	100	Em operação
20	Argentina-Uruguai	1386	Em operação
21	Brasil-Uruguai	70	Em operação
22	Brasil-Uruguai	500	Em construção
23	Argentina-Chile	633	Em operação

Neste sentido, a integração elétrica no continente ainda é bastante incipiente uma vez que a maioria das linhas de transmissão está relacionada ao comércio de curto-prazo de eventuais excedentes de eletricidade nos países. Quando os países consideram os intercâmbios apenas como uma via de mão única para a importação de energia elétrica limitam o potencial de otimização dos recursos regionais e, consequentemente, os benefícios da integração. Há estudos de viabilidade socioambiental e econômica em curso para avaliar a construção de usinas binacionais e de linhas de transmissão associadadas por todo o continente (IIRSA, 2015).

Todavia, existem muitas barreiras à expansão da integração elétrica, tais como a ausência de infraestrutura de transmissão, diferentes regulamentações dos setores elétricos e a escassez de recursos financeiros para os projetos (Hira and Amaya, 2003; Rodrigues, 2012). Sauma *et al.* (2011) destaca quarto barreiras e assimetrias que devem ser superadas para uma maior integração elétrica na América do Sul.

1. *"It is needed a higher institutionalization for: (i) harmonizing the regulatory frameworks, (ii) international operations coordination, and* ***(iii) coordination in the planning of the national interconnected systems and the national plans.***

2. *The incentives scheme to invest in international links must be revised. Regional electricity integration requires a system of remuneration (through transmission tariffs or the transfer of transmission rights), within a concept of the ‘‘regional grid’’, to incentivize these investments.*
3. *It is needed to solve some asymmetries for opportunity transactions such as variations of opportunity power prices among importer and exporter countries and the distribution of the congestion rents generated by the opportunity transactions.*
4. ***The regional integration requires establishing some type of long-term contracts,** which allows long-term transactions among market agents, incentivizes investors of interconnections, and guarantees the local supply security”.*

A metodologia que será apresentada no item 2 deste trabalho pretende contribuir, parcialmente, para a superação da primeira e da quarta barreira destacadas acima.

O aumento da coordenação entre os países pode contribuir para o desenvolvimento econômico da América do Sul, trazendo maior estabilidade política, além de fortalecer a União Sul-americana de Nações (UNASUL) e demais instituições para a integração energética regional, dentre elas a Comissão para Integração Energética Regional (CIER), a Organização Latino-Americana de Energia (OLADE) e a Iniciativa para a Integração de Infraestrutrura Regional Sul-Americana (IIRSA).

O Brasil possui um papel natural de líder no processo de integração dos sistemas elétricos do continente uma vez que possui fronteiras com quase todos os países do continente, exceto Chile e Equador, e conhecimento na operação do Sistema Interligado Nacional (SIN), que possui escala continental (ONS, 2015a). O país é o maior produtor e consumidor de energia elétrica, respectivamente, 51% e 56% (CIER, 2015) e apresenta a maior população do continente, aproximadamente 196 milhões de habitantes ou 49% do total (PRB, 2013). Além disso, possui a maior economia da região, com capacidade financeira para financiar projetos de integração elétrica, considerados estratégicos pelo governo brasileiro. Ao longo das décadas de 1990 e 2000 foram assinados vários acordos internacionais entre os governos dos países visando maior cooperação energética e a viabilização de novos empreendimentos não necessariamente associados a usinas binacionais (Moura *et al.*, 2012).

2. Metodologia

A primeira proposta apresentada para esta tese ocorreu em março de 2014, durante o processo de qualificação ao doutorado no Programa de Planejamento Energético. Tratava-se da modelagem dos sistemas elétricos dos países do Mercado Comum do Sul (MERCOSUL) – Argentina, Brasil, Paraguai, Uruguai e Venezuela – visando identificar o potencial de comércio internacional de energia elétrica entre os países no longo-prazo, considerando uma integração produtiva, em vez de apenas uma integração comercial baseada na comercialização de sobras de energia elétrica. Ademais, propunha-se que a modelagem utilizasse também uma abordagem de Planejamento Energético Integrado (PEI) dos diversos recursos energéticos disponíveis no continente para a geração elétrica.

Dentre os possíveis instrumentos passíveis de serem utilizados no processo de modelagem, surgiu a ideia de se implementar um modelo via um ambiente de planejamento da expansão de sistemas energéticos de longo-prazo, aberto e gratuito, recentemente disponibilizado na literatura: o ***Open Source Energy Modelling System – OSeMOSYS*** (Howells *et al.*, 2011). A partir dessa ideia, foram então feitos contatos com a divisão de Análise de Sistemas Energéticos do Instituto Real de Tecnologia[1] de Estocolmo, Suécia, onde está a equipe de pesquisadores que desenvolve o OSeMOSYS, para que o autor da presente tese atuasse como pesquisador visitante naquela instituição entre setembro de 2014 e agosto de 2015[2], o que acabou acontecendo.

Além disso, foi também sugerido que a análise não ficasse limitada apenas aos países membros do MERCOSUL, mas, sim, fosse expandida para todos os países da América do Sul.

Como enfoque adicional, surgiu a ideia de que na análise do comércio de eletricidade no continente fosse empregada a abordagem da teoria dos jogos cooperativos, a partir do **cálculo do Valor de Shapley**, de forma a estimar a

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[1] Em inglês: *division of Energy Systems Analysis (dESA), Royal Institute of Technology* (em sueco: *Kungliga Tekniska Högskolan - KTH*).

[2] O estágio de doutorado com pesquisador visitante foi possível por meio do Programa de Doutorado Sanduíche no Exterior (PDSE) da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) do Ministério da Educação (MEC) do Brasil.

contribuição potencial de cada país para o comércio internacional de energia elétrica e repartir equitativamente os benefícios da integração entre os países, incentivando, assim, ações cooperativas para o planejamento da expansão dos sistemas elétricos de forma integrada no continente.

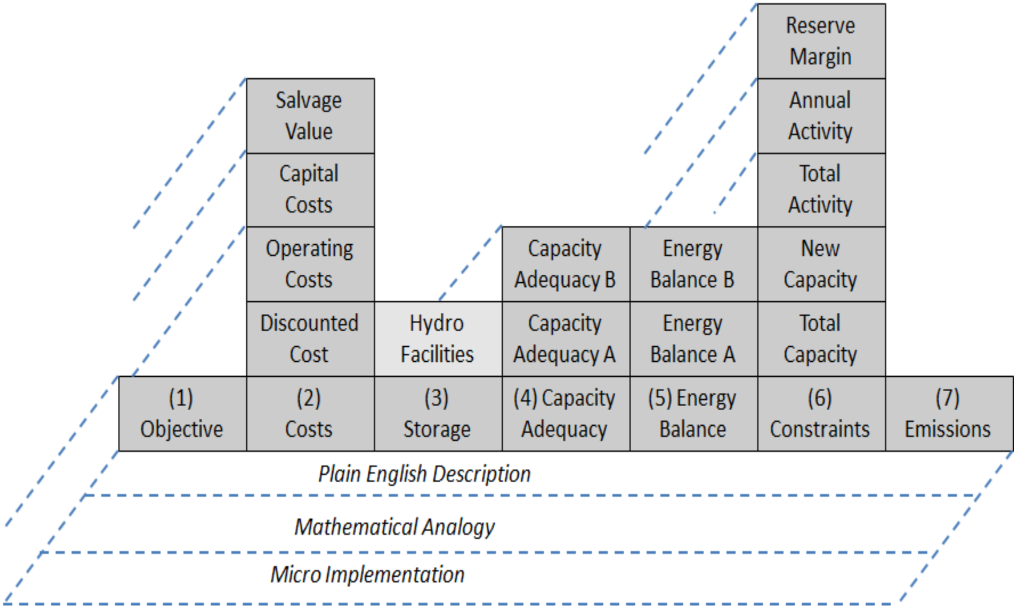
Finalmente, durante o estágio na Suécia foi sugerido que a modelagem deveria apresentar também características relacionadas às restrições de emissões de gases de efeito estufa pelos setores elétricos dos países sul-americanos, sobretudo em função do atual contexto de mudanças climáticas em curso no planeta.

Dessa forma, a metodologia aqui proposta baseia-se fundamentalmente em duas etapas principais brevemente descritas a seguir e que serão detalhadas nos itens 2.1 e 2.2 desta tese. Primeiramente, foi realizada a partir do ambiente OSeMOSYS uma modelagem do planejamento da expansão dos sistemas elétricos dos países sul-americanos, considerando a infraestrutura existente assim como aquela apresentada em planos de expansão nacionais. Diferentes políticas de integração elétrica foram descritas e modeladas em cenários, com horizonte de planejamento de até 45 anos (2013-2058). Em segundo lugar, os resultados da modelagem indicam, entre outras informações, os potenciais de comércio internacional de eletricidade no continente no longo-prazo, dados essenciais para a etapa seguinte da metodologia proposta. Estes potenciais são analisados por intermédio da teoria dos jogos cooperativos de forma a identificar o poder de barganha dos países utilizando o Valor de Shapley, uma informação sensível para a elaboração de contratos de longo-prazo de compra e venda de eletricidade, e que pode auxiliar formuladores de políticas durante negociações internacionais.

2.1 Open Source Energy Modelling System (OSeMOSYS) and the South America Model Base (SAMBA)

O código original do OSeMOSYS foi escrito por Howells *et al.* (2011), em uma linguagem de programação aberta e gratuita *(GNU Mathprog)*. O modelo utiliza o solver *GNU Linear Programming Kit (GLPK)* para problemas de programação linear de grande escala, é relativamente de fácil aprendizado e está bem documentado no seu *website* (www.osemosys.org), onde estão disponíveis fóruns para esclarecer problemas enfrentados por seus usuários. O código do modelo está disponível para *download* no *website,* assim como a nova estrutura de modelagem desenvolvida nesta tese denominada ***South America Model Base – SAMBA***, sem a necessidade de gastos de aquisição e manutenção. Diferentemente de outros modelos de planejamento da expansão, como MARKAL/TIMES, MESSAGE, PRIMES, EFOM e POLES, o código é aberto, flexível e gratuito. A estrutura do OSeMOSYS corresponde a "blocos" com distintas funções, os quais estão subdivididos em diferentes níveis de abstração, conforme apresentado na Figura 2.

Figura 2: "Blocos" do OSeMOSYS e níveis de abstração
Fonte: Howells *et al.* (2011)



Uma breve descrição de cada "bloco" do código é apresentada a seguir.

O objetivo (Bloco 1 da Figura 2) calcula o menor Valor Presente Líquido (VPL) de um sistema energético para atender a uma demanda exógena de energia informada pelo usuário. O sistema é representado por tecnologias, as quais produzem ou demandam determinados filões energéticos. No segundo bloco são contabilizados os custos de cada tecnologia, sejam operacionais (OPEX) ou de expansão (CAPEX), para cada ano na região modelada. Cada tecnologia pode apresentar uma taxa de desconto geral ou uma específica para calcular o VPL.

A modelagem de armazenamento de energia (por reservatórios hidroelétricos ou baterias) está presente no Bloco 3 e permite a carga e descarga de energia durante uma fração do tempo (*Time Slice*) definida, desde que os níveis permaneçam entre valores mínimos e máximos pré-definidos pelo usuário. Quanto mais frações de tempo forem consideradas, mais apurados serão os cálculos de armazenamento. Por outro lado, a complexidade da modelagem aumentará devido ao incremento das informações necessárias, que por sua vez aumentará o esforço computacional para encontrar as soluções de custo mínimo[3].

A resolução temporal do modelo corresponde aos anos consecutivos, divididos em frações de tempo, as quais representam um período do ano com características de carga específicas. As frações de tempo na primeira versão do OSeMOSYS são consideradas de forma independente no processo de otimização, uma característica dos modelos de planejamento de sistemas energéticos de longo-prazo para os quais a interdependência temporal não é significativa.

Entretanto, uma vez que a ordem cronológica é fundamental para a modelagem dos níveis dos reservatórios hidroelétricos, a versão SAMBA do código incorpora uma abordagem cronológica das frações de tempo. Neste sentido, o número de frações de tempo no OSeMOSYS SAMBA foi estabelecido de forma a se obter uma representação mais adequada da variação mensal da disponibilidade de recursos hídricos, uma vez que a geração hidroelétrica possui um papel fundamental nos sistemas elétricos da maioria dos países da América do Sul.

A adequação das necessidades de capacidade está no Bloco 4, de forma a assegurar que capacidade existente seja suficiente para uma determinada tecnologia atender ao seu consumo e/ou produção requeridos em cada fração do tempo em uma base anual. O Bloco 5 está relacionado ao Balanço de Energia, tais como os níveis de operação durante o ano e nas frações do tempo (taxa de atividade, consumo de energia, produção de energia, e emissões para uma dada tecnologia).

Várias restrições podem ser estabelecidas na modelagem (Bloco 6), por exemplo, limites de capacidade total de uma tecnologia disponível em um ano e região, assim como máximos e mínimos para investimentos em nova capacidade. Outro exemplo é a restrição para o atendimento de margens de reserva de eletricidade, para a qual algumas tecnologias são selecionadas como provedoras de capacidade de reserva. Finalmente, para contabilizar as emissões de tecnologias (Bloco 7), o usuário pode inserir uma taxa de emissão por unidade de atividade de uma tecnologia a qual multiplicada pela taxa de

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[3] O tempo de máquina necessário para computar um cenário do OSeMOSYS SAMBA é de aproximadamente quatro horas (uma hora para montar o problema de programação linear e três horas para o algoritmo de otimização - CPLEX - encontrar a solução de custo mínimo). Foi utilizado um computador com 64 Gb de RAM para um horizonte de planejamento de 51 anos (2013-2063) e 48 frações de tempo em cada ano.

atividade anual irá prover dados de emissões anuais. Uma descrição completa e detalhada das características do OSeMOSYS é apresentada por Howells *et al.* (2011) e o código utilizado no OSeMOSYS SAMBA está disponível no Apêndice A.

A estrutura flexível do código permite facilmente ao usuário desenvolver novos blocos de funcionalidade, retirar aqueles que não são necessários em um dado ensaio (com melhoras no desempenho computacional) e até mesmo alterar os blocos existentes para considerar características específicas de uma dada aplicação. Dessa forma, o OSeMOSYS disponibiliza uma abordagem transparente e útil para a modelagem do planejamento da expansão de sistemas elétricos.

Neste contexto, cenários foram elaborados neste trabalho para identificar a dinâmica de longo-prazo do planejamento dos sistemas elétricos da América do Sul, considerando os planos de expansão de onze países. A modelagem realizada no OSEMOSYS SAMBA identifica os cenários com as melhores soluções de custo mínimo e fornece informações que podem auxiliar na superação de barreiras técnicas e econômicas à integração de fontes renováveis com potenciais de mercado. A análise dos cenários modelados provê informações relevantes quanto à evolução do mix de geração elétrica e os potenciais de comércio internacional de eletricidade a partir de distintas perspectivas nacionais e suas políticas energéticas de integração relacionadas.

2.2 Teoria dos jogos cooperativos e o cálculo do Valor de Shapley

Teoria dos jogos trata do estudo de situações estratégicas, ou simplesmente, um jogo. Considera problemas de decisão com vários jogadores envolvidos, cujas decisões impactam-se mutualmente. Os jogos podem ser divididos em cooperativos e não cooperativos. Os atores participantes de jogos não cooperativos são indivíduos, grupos empresas, governos, que atuam de acordo com seus próprios interesses (unilaterais). A abordagem não cooperativa permite o desenvolvimento de ferramentas úteis para a análise de jogos. Uma clara vantagem dessa abordagem reside na capacidade de modelar como detalhes específicos da interação entre diferentes atores podem impactar no resultado final de um jogo. Entretanto, uma limitação está na alta sensibilidade dos resultados aos detalhes da relação. Por essa razão, é importante também utilizar abordagens mais abstratas que tentem obter conclusões que sejam menos dependentes de tais detalhes. A abordagem cooperativa representa uma dessas tentativas e é aquela considerada neste trabalho (Osborne e Rubinstein, 1994; Medina, 2012).

Em jogos cooperativos, os jogadores cooperam entre si de forma a alcançar um objetivo comum, sendo caracterizados por acordos de ação conjunta. O cálculo do Valor de Shapley[4] aborda a distribuição justa dos benefícios obtidos em função do comportamento cooperativo dos jogadores participantes (Straffin, 1993). Estima-se a contribuição esperada de cada jogador para o ganho total da grande coalizão, aquela formada por todos os jogadores. Todas as coalisões entre os jogadores do jogo devem ser igualmente prováveis, com os jogadores sendo incorporados de forma aleatória. O valor calculado pode ser compreendido como o poder de barganha de um jogador, uma vez que representa a contribuição média que o mesmo proporciona à coalizão, e equivale à quantidade justa que este jogador deveria receber na divisão dos benefícios entre todos os jogadores (Naveiro *et al.*, 2009).

Foram identificados alguns estudos que mostram como o conceito do Valor de Shapley aplicado ao setor energético pode auxiliar na distribuição justa dos benefícios obtidos a partir de um comportamento cooperativos entre os agentes envolvidos (Pierru, 2007; Naveiro *et al.*, 2009; Medina, 2012; Banez-Chicharro *et al.*, 2017). Entretanto, não é de nosso conhecimento estudos que utilizem o conceito do Valor de Shapley aplicados ao processo de integração de sistemas elétricos, ou seja, à divisão justa dos ganhos obtidos a partir da energia elétrica comercializada em linhas de transmissão internacionais entre países que se propõem a cooperar e realizar um planejamento da expansão da capacidade instalada de forma conjunta.

Vários autores apresentam uma descrição detalhada dos axiomas necessários para calcular o Valor de Shapley, com destaque para Osborne e Rubinstein (1994), Kleinberg e Weiss (1986). Medina (2012) e Straffin (1993) descrevem brevemente os axiomas da seguinte forma:

- Eficiência: A soma dos valores de Shapley de cada jogador é equivalente ao valor da grande coalizão;

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[4] Lloyd Stowell Shapley (2 de junho de 1923 – 12 de março de 2016) foi um matemático estadunidense, vencedor do Prêmio Nobel de economia em 2012. Seus estudos mais relevantes foram de matemática aplicada à economia e teoria dos jogos. Introduziu o conceito abordado neste trabalho, e que leva o seu nome, em 1953.

- Simetria: Dois jogadores são considerados simétricos em um jogo se possuem a mesma contribuição marginal para uma dada coalizão, e dessa forma recebem a mesma quantidade de benefícios;
- Adição: Caso dois jogos sejam combinados, então a distribuição dos benefícios deve corresponder à soma das contribuições em cada jogo; e
- Jogador nulo: se há um jogador que não adiciona valor à coalizão, ou seja, um jogador nulo, então o seu Valor de Shapley é zero. Adicionar um jogador nulo ao jogo não altera o Valor de Shapley dos demais jogadores no jogo.

Existem vários métodos para calcular o Valor de Shapley de um jogador em um jogo com n jogadores (Kleinberg *et al.*, 1985; Bilbao *et al.*, 2000; Ieong *et al.*, 2005; Conitzer *et al.*, 2004). O método utilizado neste trabalho foi apresentado por Straffin (1993) e possui como principal característica o foco em um jogador particular i e a verificação de qual a frequência e quanto este jogador contribui para a formação da grande coalizão.

Consequentemente, quando o jogador i é adicionado à coalizão S ($i \in$ S) no processo de formação da grande coalizão, a sua contribuição depende dos jogadores que já estão presentes na coalizão S, de tamanho s. O valor (v) do jogador i ou sua contribuição é $v(S) - v(S - i)$, a qual ocorre para aquelas ordens de entrada nas quais i é precedido pelos $s - 1$ outros jogadores em S, e seguido pelos $n - s$ jogadores que ainda não estão em S. Uma vez que isto acontece $(s-1)!\,(n-s)!$ vezes, é possível escrever o Valor de Shapley para o jogador i da seguinte forma:

$$\varphi_i = \frac{1}{n!}\sum_{i \in S}(s-1)!\,(n-s)!\,[v(S) - v(S-i)] \qquad (onde\ s\ \text{é}\ o\ tamanho\ de\ S)$$

Dessa forma, para realizar o cálculo do Valor de Shapley de um jogador particular i deve-se somar o valor das 2^{n-1} coalizões S que contém o jogador i.

Nos cenários SAMBA, onde integração elétrica envolve onze países (jogadores), a contribuição de um dado país foi calculada considerando cada uma das 1024 (ou 2^{10}) coalizões possíveis que o jogador era adicionado, de forma a identificar o seu Valor de Shapley. Este cálculo foi realizado com o auxílio de um algoritmo desenvolvido no Scilab (2016) disponível no Apêndice B.

O poder de barganha de cada país pode ser interpretado como a importância que um país possui em um grupo de países. Por exemplo, como o Brasil é capaz de influenciar países vizinhos na construção de projetos estratégicos de usinas hidroelétricas de forma a ampliar a importação de energia elétrica. O benefício da grande coalizão dos países corresponde à eletricidade comercializada em todas as linhas de transmissão internacionais do continente, o qual deve ser distribuído de forma justa entre os países, em função de suas respectivas contribuições. Dessa forma, quanto maior a contribuição de um país para o comércio internacional, maior será o seu poder de barganha.

A aplicação do cálculo do valor de Shapley ao processo de integração elétrica na América do Sul, por meio da divisão dos benefícios oriundos de um planejamento da expansão integrado, pode estimular maior cooperação entre os países com ganhos relacionados ao aumento da segurança energética e do uso ótimo de recursos energéticos.

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Os três ensaios apresentados nesta tese (capítulos 3, 4 e 5) foram submetidos a revistas internacionais que consideram estudos relacionados ao Planejamento Energético. A seguir apresenta-se uma breve descrição desses ensaios:

- Primeiro ensaio – Analisa a perspectiva brasileira do processo de integração elétrica utilizando o OSeMOSYS SAMBA – South America Model Base – e o poder de barganha dos países vizinhos, por intermédio de uma abordagem da teoria dos jogos cooperativos;
- Segundo ensaio – Discute o potencial de exportação de eletricidade da Bolívia e o poder de barganha desse país por meio da modelagem no OSeMOSYS SAMBA;
- Terceiro ensaio – Apresenta o potencial de geração renovável em grande escala na América do Sul frente as *Nationally Determined Contributions* a partir da modelagem de um cenário no OSeMOSYS SAMBA que contempla essas alternativas.

A ordem de exposição dos ensaios foi estabelecida em função dos desenvolvimentos das aplicações do modelo OSeMOSYS SAMBA e do cálculo do poder de barganha, desde uma descrição mais detalhada de todos os parâmetros envolvidos na modelagem sob a perspectiva brasileira (primeiro ensaio), passando por uma comparação metodológica do potencial de exportação de eletricidade apresentado pelo governo boliviano (segundo ensaio), e por último, uma aplicação com foco nas políticas de emissões dos setores elétricos dos países da América do Sul, a partir de compromissos nacionais firmados no Acordo de Paris em 2015.

3. Primeiro ensaio: A Brazilian Perspective of Power Systems Integration Using OSeMOSYS SAMBA - South America Model Base - and the Bargaining Power of Neighbouring Countries: a Cooperative Games Approach[5]

3.1 Abstract

This paper intends to contribute to a better understanding of both advantages and drawbacks of power systems interconnection processes between Brazil and its South American neighbours. Based on data available in national and international reports, three scenarios for the power supply sector expansion were modelled in OSeMOSYS. The Brazilian perspective of power integration considers funding strategic hydro projects in Argentina, Bolivia, Guyana and Peru. An alternative to the power integration process considers higher penetration of distributed photovoltaics and biogas power plants as well as lower hydro capacity expansion in Brazil. Features related to costs, carbon emissions, hydro reservoirs, technological performance, electricity demand, population growth, time zones and reserve margin were considered. The comparison of different scenarios provides insights regarding the contribution of renewable energy generation and sheds light on cross-border trade perspectives between Brazil and other countries in South America. Using a cooperative games approach, the bargaining power of each country (player) was calculated by applying the Shapley value concept. Argentina, Brazil, Paraguay, Peru and Guyana have the largest bargaining power, either as exporter or importer.

3.2 Highlights

We model the long-term dynamics of power systems integration in South America.
Two scenarios simulate the evolution of cross-border electricity trade.
A cooperative game theory approach based on the Shapley value concept was used.
Brazil, Peru, Paraguay, Guyana and Argentina have the largest bargaining power.
The proposed methodology may support policy makers during international negotiations.

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[5] Artigo submetido para a revista Energy Policy em Março de 2016.

3.3 Keywords

Power systems integration; OSeMOSYS SAMBA; Cross-border electricity trade; Cooperative Games; Shapley Value;

3.4 Introduction

South American countries have diverse and abundant energy resources ranging from oil, natural gas, coal and biomass to considerable potentials of other renewable sources, such as large hydro, wind and solar. These resources are not evenly distributed. This asymmetry is precisely what underlines the potential for developing important energy exchanges within the continent, mainly through hydro-wind power synergies. Studies about modelling power integration in South America exist in the literature (Sauma *et al.*, 2011; Ochoa *et al.*, 2013), but focus on a particular group of countries in the Andean region.

In 2012, electricity generation from renewable sources in South America represented 69% of the total, which is significantly higher than the global average of 21% (CIER, 2013; IEA WEO 2014). However, due to structural reforms in the electricity sectors in the 1990s the continent is becoming increasingly dependent on thermal generation (Arango and Larsen, 2010). This is particularly true in Brazil, the largest producer (51%) and consumer (56%) of electricity of the continent, where there has been a steady increase in the installed capacity of thermal power since 2003 (EPE, 2014a; CIER, 2013).

The share of conventional installed thermoelectric capacity in Brazil is 27% of the total, but conventional thermal generation represented only 16% of the total electricity generation in 2012 (D’Araujo, 2012). This means that the operation of the Brazilian electricity system prioritizes the (lower cost) generation of hydro plants with reservoirs. However, the backup generation provided by the water stored in reservoirs will be relatively lower than nowadays, because new hydro in Brazil are essentially of the run-of-the river type, which means less flexibility for hydroelectric generation. The objective of such expansion policy is to meet current society environmental concerns caused by hydro plants in the Amazon region, where the largest remaining hydro potential is located. Actually, the storage capacity of existing reservoirs are being used to its limits, thus impairing the flexibility they provide (EPE, 2014b). In addition, the long-term planning of the Brazilian electricity sector carried out by the state owned company Empresa de Pesquisa Energética (EPE) is reluctant to increase the number of conventional thermal plants — such as Natural Gas Combined Cycle (NGCC) — to supply the base of the power demand, a move that could circumvent the decline in the flexibility of reservoirs.

Despite the decrease in flexibility, the storage capacity of Brazilian reservoirs was sufficient, in 2012, to supply about 4.5 months of the national consumption monthly average (EPE, 2013). A storage capacity of this magnitude allows for the integration of electricity generation from other renewable sources with higher levels of intermittency, such as thermal biomass, wind and solar power.

The electricity demand is expected to increase steadily across South America during the next decades, as its low per capita consumption (1.871 kWh per year) is about one third of the average value for countries such as Portugal, Spain and Italy, which centres around 5.500 kWh per year (World Bank, 2015). Besides, there are significant disparities among countries, with per capita annual consumption ranging from 569 kWh in Guyana to 3.795 kWh in Chile as shown in Table 2 (CIER, 2013).

Table 2 - South America population and electricity consumption in 2013
Source: Own elaboration, based on PRB (2013) and CIER (2013)

Country	**Population**	**Electricity Consumption[a] (TWh)**	**Electricity Consumption / population (kWh per Capita)**
Argentina	41.3	113.0	2735
Bolivia	11.0	6.3	574
Brazil	195.5	464.1	2374
Chile	17.6	66.8	3795
Colombia	48.0	54.5	1134
Equador	15.8	20.9	1324
Guyana	0.8	0.5	569
Paraguay	6.8	9.0	1324
Peru	30.5	35.8	1174
Uruguai	3.4	8.6	2516
Venezuela	29.7	91.1	3067

[a] Gross production + imports exports transmission/distribution losses

The Brazilian government has shown interest in funding and developing joint-venture projects in the electricity sectors of neighbouring countries, particularly hydropower plants and grid interconnectors (MME, 2006). However, short-term macroeconomic and political conditions in Brazil are as yet not favourable to funding hydro dams abroad and may postpone the assessment of such projects, even though they remain viable in the long-term. Another impact of the economic crisis in Brazil was the weakening of electricity demand since 2015 (a decrease of 2.1% and 0.9%, respectively, in 2015 and 2016) (EPE, 2017). Despite short-term conditions, Brazil might still lead the process of power systems integration in the region that goes beyond occasional electricity surplus exchanges. Environmental and feasibility studies are being carried out for the construction of hydropower plants and transmission lines with Argentina, Uruguay, Venezuela, Bolivia, Peru and Guyana.

Taking into consideration all transmission lines – whether or not associated to binational hydroelectric plants – there were 18 international interconnections in operation in 2013 (CIER, 2015). The expansion of international grid connections may foster an increase in renewable generation, with important synergistic gains due to the seasonal variability of renewable sources and the differences in the shape of load curves throughout the region. Nevertheless, the long-term consequences of Brazilian plans for cross-border exchanges remain unclear from a broader perspective. One example of the changing conditions in the region is the transmission lines, non-associated to hydro projects, built between Brazil-Argentina and Brazil-Venezuela, which were intended for importation to Brazil of low cost electricity surplus. This actually happened in the first years of operation, but from 2010 onwards the situation reversed and Brazil became an important exporter as well (Rodrigues, 2012).

To take into account such possible variations, three scenarios were developed for the expansion of the South American power supply sector, with a focus on the long-term (2013-2058). Although the scenarios consider upper limits on carbon dioxide emissions for the power sector, a comparison between them provides insights on how renewable energy generation is affected by the power systems integration. Additionally, using a cooperative games approach with the application of the Shapley value concept, the bargaining power of each country (player) was calculated for all SAMBA scenarios. This allows an analysis of how an asymmetrical bargaining power — and distortions of a country's payoffs vis-à-vis its Shapley value — impacts the continent's trade perspectives.

Several studies have shown how the Shapley value concept applied to the energy sector might help in devising schemes for the fair distribution of the benefits attained from cooperation behaviour among agents (Pierru, 2007; Naveiro *et al.*, 2009; Medina, 2012; Banez-Chicharro *et al.*, 2017). Nevertheless, to our knowledge there are no studies which have applied the Shapley value to the fair distribution of benefits of power system integration processes. This paper intends to help filling this gap by proposing a methodology that may provide important information to support policy makers in international negotiations, thus considerably reducing incentives to non-cooperative actions.

In order to achieve this objective, section 2.5 presents the proposed methodology and the tools used to implement it, while section 2.6 presents the available power generation resources of South America. The 2.7 and 2.8 sections introduce and discuss the basic premises used and the results obtained for both scenarios. In the 2.9 section a cooperative game theory approach is used to identify the importance of all interconnections. Conclusions of this study as well as future research are provided in section 2.10.

3.5 Methodology

The study comprises a descriptive study of South America power sector using a quantitative approach in which all existing grid interconnections between countries were included. The base year is 2013[6], with three scenarios built for the period 2013-2058[7].

The modelling tool chosen was the Open Source energy Modelling System - OSeMOSYS, an optimization software for long-term energy planning. The OSeMOSYS does not use proprietary software or commercial programming languages and solvers, nor does it have upfront financial investment requirements. Further, it is an open source model structured in blocks of functionality that allow easy modifications to the code. A complete and detailed description of OSeMOSYS features is presented by Howells *et al.* (2011) as well as in Appendix A. Despite its flexibility and broad scope, it does not require a significant learning curve and time commitment to build and operate as compared to long established energy systems models, which do not properly include sequential time, big regions and geographical detail (Després *et al.*, 2015). In addition, the majority of long-term energy systems planning models are not as accurate when used as power system models, due to the lack of modelling tools to adequately represent

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[6] Due to the lack of open source annual sectoral reports as well as the delay among countries' data publication, the task of finding a common base year is challenging. As for the present study, the most updated representation of the power system of the eleven countries was possible only by considering data from 2013 onwards.

[7] To avoid border effects, results and data for the last five years (2059-2063) were not included.

the increasing penetration of renewable energy technologies. Since its publication in 2011, many developments in OSeMOSYS were made to allow a better representation of renewable sources with greater intermittency (Welsch *et al.*, 2012; Welsch *et al.*, 2014a Welsch *et al.*, 2014b; Welsch *et al.*, 2015).

The implementation of the South America power sector in OSeMOSYS was named SAMBA, an acronym for South America Model Base. It was developed from the basic version of the code (Howells *et al.*, 2011), with the following additions: (1) storage constraints (Welsch *et al.*, 2015); (2) reserve margins for each country (Cervigni *et al.*, 2015); and (3) annual constraints for production inflexibility applied to generation technologies, which was developed specifically for the implementation of SAMBA. The SAMBA version of the code is available at www.osemosys.org (OSeMOSYS, 2015).

As mentioned before, three scenarios were implemented:

- Reference Trade SAMBA (RTS): based on national expansion plans projected by governments (short, medium and long-term) with the existing 23 international power interconnections (Table 3);
- Integration Trade SAMBA (ITS): based on the reference scenario with the addition of strategic large hydro projects and associated transmission lines now under evaluation by the Brazilian government (Table 4, EPE 2014b).
- Alternative Trade SAMBA (ATS): based on the reference scenario with the addition of distributed photovoltaic in Brazil, lower hydro expansion capacity and reduced investment costs of biogas (from second generation) power plants.

An extensive bibliographical search was carried out to identify power sector features of eleven countries and is presented in Appendix C. The Brazilian power system was modelled with four subsystems (North, Northeast, South and Southeast) for a better representation of its continental size. The energy resource potentials and reserves in every South American country were included, and their production growth rates were taken from long-term plans drawn up by their respective national governments.

The sixteen electricity generation technologies considered are: large and small (< 30 MW) hydroelectric plants[8]; bagasse thermal power (first and second generation biofuels); geothermal; wind farms (on-shore and off-shore); large solar (photovoltaic and concentrated); distributed photovoltaic; coal (pulverized and Clean Coal with Carbon Capture and Storage), fuel oil thermal plants; natural gas (open cycle and NGCC); and nuclear plants.

Table 3 - Total installed capacity of international transmission lines in South America
Source: based on CIER (2013)

Interconnections	Total Installed Capacity (MW)
Argentina - Chile	633
Argentina - Brazil South	2200
Argentina - Paraguay	3000
Argentina - Uruguay	3376
Brazil North - Venezuela	200
Brazil Southeast - Paraguay	6100
Brazil South - Uruguay	570
Colombia - Ecuador	363
Colombia - Venezuela	380
Ecuador - Peru	100

Table 4 - Strategic large hydro projects for Brazilian government
Source: based on EPE (2014b)

Strategic Hydropower Projects	Interconnections	Total Installed Capacity (MW)
Inambari Dam and Peruvian Amazon Dam Complex	Peru - Brazil Southeast	7200
Middle Mazzaruni and Upper Mazzaruni Dams	Guyana - Brazil North	4500
Garabi and Panambi Dams	Argentina - Brazil South	2200
Cachuela Esperanza Dam	Bolivia - Brazil Southeast	800

3.6 South America renewable and non-renewable resources

South America is an energy resource rich continent, in renewable and non-renewable resources as well. The following section presents and analyses the different types of available resources. Table 5 presents the natural gas, shale gas, coal, crude oil and uranium reserve levels for each country. Both Venezuela and Ecuador have large crude oil reserves and are members of the Organization of the Petroleum Exporting Countries (OPEC). Brazil, despite not being an OPEC member, is an important crude oil producer with deep-water reserves located along its coastline. Since 2007, large resources have been discovered and exploited in pre-salt area (EPE, 2014b).

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[8] This definition of Small Hydro Plants follows the Brazilian power sector legislation (ANEEL, 2015a).

Table 5 - Reserves of Non-renewable resources on South America in 2013
Source: based on US EIA (2015), OLADE (2013) and EPE (2014a)

Country	Natural Gas Trillion Cubic Feet	Shale Gas[a] Trillion Cubic Feet	Coal Billion tons	Oil Billion Barrels	Uranium Million tons U3O8
Argentina	13.0	802	0.6	2.8	19
Bolivia	9.9	-	0.0	0.2	-
Brasil	15.0	245	7.3	15.0	278
Chile	3.5	-	0.2	0.2	-
Colombia	4.7	-	7.4	2.4	-
Equador	0.3	-	0.0	8.2	-
Guyana	0.0	-	0.0	0.0	-
Paraguay	0.0	-	0.0	0.0	-
Peru	12.0	-	0.0	0.6	-
Uruguay	0.0	-	0.0	0.0	-
Venezuela	195.0	-	0.5	298.0	-

[a] Unproved technically recoverable shale gas resources

The largest natural gas reserves are located in Venezuela, Brazil, Argentina, Peru and Bolivia. Brazil and Chile are the two main importers and are connected to Bolivia and Argentina, respectively, through pipelines with large capacity, as shown in Table 6 (CIER, 2013). Argentina, Brazil and Chile built an import infrastructure for Liquefied Natural Gas (LNG) terminals as shown in Table 6. Since the first power sector reforms in the 80s, natural gas for generating electricity in the continent has had an increasing importance due to many reasons, especially economic and generation reliability (Arango and Larsen, 2010).

Table 6 - International infrastructure of natural gas in South America
Source: based on CIER (2013) and OLADE (2013)

Countries	Infraestructure	Capacity Million Cubic Meters / Day
Argentina to Chile	Pipeline	41.5
Argentina to Brazil	Pipeline	12.5
Argentina to Uruguay	Pipeline	4.5
Bolivia to Argentina	Pipeline	8.2
Bolivia to Brazil	Pipeline	32.8
Venezuela to Colombia	Pipeline	4.2
Argentina	LNG Terminal	29.5
Brazil	LNG Terminal	28
Chile	LNG Terminal	20.5

Brazil and Colombia present the largest coal reserves on the continent, although with different quality grades. Brazilian lignite and subbituminous coal quality is poor and consumed as steam coal in thermal plants in the South, where reserves are located (USGS, 2015).

Brazil and Argentina produce uranium ore from national reserves. Although they have followed distinct technology routes, both countries have and operate nuclear plants. Brazil exports its uranium ore and imports enriched uranium to fuel its Pressurized Light-Water Reactors (PLWR), since a large scale national production has not been achieved (Carvalho *et al.*, 2009; Cabrera-Palmer *et al.*, 2008). Argentina fuels its Canadian Deuterium-Uranium Pressurized Heavy-Water Reactors (CANDU PHWR) with national uranium ore and heavy-water (CNEA, 2015b).

Concerning renewable resources, the largest hydro potentials are in Brazil, Colombia and Peru, and the latter two countries have not yet exploited more than 10% of them (Table 7). The region main source is hydropower, which accounts for 100% of the electricity generated in Paraguay, 75% in Brazil and 71% in Colombia (CIER, 2013).

Table 7 - Hydro and geothermal potential of South America
Source: based on OLADE (2013)

Country	Large Hydro			Small Hydro[b] Potential (GW)	Geothermal Potential (GW)
	Total Potential (GW)	Exploited (GW)	Maximum Exploited[a] Potential (GW)		
Argentina	40.0	25%	26.4	2.0	2.0
Bolivia	40.0	1%	26.4	2.0	2.0
Brazil	260.0	31%	171.6	13.0	n.a
Chile	25.0	22%	16.5	1.3	2.0
Colombia	93.0	10%	61.4	4.7	2.0
Ecuador	25.0	9%	16.5	1.3	2.0
Guyana	7.0	0%	4.6	0.4	n.a
Paraguay	12.5	70%	8.8	0.6	n.a
Peru	60.0	6%	39.6	3.0	3.0
Uruguay	1.8	85%	1.5	0.1	n.a
Venezuela	46.0	32%	30.4	2.3	1.0

[a] Limited up to 66% of total potential except for Paraguay and Uruguay

[b] Assumed 5% of total large hydro potencial

The unexploited large hydro potential of neighbouring countries is increasingly the subject of discussions among Brazilian power sector specialists, in order to better understand the social, environmental, technical and economic impacts related to possible projects (Raineri *et al.* 2014; Castro, 2010). Synergies between wet and dry seasons in different hydro basins — in Northern Brazil and South-eastern Venezuela — could increase energy security, although long-term impacts and trade benefits are unknown (MME, 2006).

In Brazil, the remaining large hydro potential is in the Amazon region, but new projects have been criticized because of their environmental and social impacts, such as those caused by the Belo Monte dam. This is one of the reasons why the Brazilian government is interested in funding strategic hydropower projects in neighbouring countries, so as to make possible the importation of large amounts of low cost electricity.

Another important unexploited potential for electricity generation is the geothermal resource located mainly in Andean countries, such as Bolivia, Colombia and Ecuador who foresee the use of geothermal plants in their medium-term expansion plans (AE, 2012a; MEER, 2012; UPME, 2013).

3.7 Basic assumptions

This section describes and explains the basic assumptions used to model the South American power sector in the RTS, ITS and ATS scenarios.

3.7.1 Electricity demand

For all scenarios, the total electricity demand for each country is assumed to increase at an annual rate compatible to reach a per capita consumption of 5.500 kWh per year by 2058, which is comparable to the 2012 consumption level of developed countries such as Spain (5530 kWh), Italy (5515 kWh) and Greece (5380 kWh) (World Bank, 2015). This assumption aims at considering the social welfare gain arising from higher electricity consumption, given the disparities in electricity consumption in the continent (Table 1), since this is an important factor in the Human Development Index (HDI) of nations (Niu *et al.*, 2013).

The annual electricity demand profile for each country was described using 48 time slices (one day type per month of the year, split into four six hours periods). The more time slices the better for representing renewable electricity production seasonality in OSeMOSYS, as in the case, for instance, of the monthly breakdown, which is significant given the importance of hydro generation in the continent.

Electricity demand profiles in Argentina, Brazil, Bolivia, Uruguay and Peru were identified using hourly demand databases from national power systems operators (ONS, 2015a; CAMMESA, 2015b; AE, 2015; COES SINAC, 2015; ADME, 2015). For Colombia, Chile, Venezuela, Guyana, Paraguay and Ecuador the only available data was the average monthly demand profile (GPL, 2015; VMME, 2014; MPPEE, 2013a; MPPEE, 2014; CDEC SING, 2012; CDEC SIC, 2013; SIEL, 2015; ARCONEL, 2014b). To overcome this lack of information, the daily profile of a neighbouring country with similar features was used to set the demand profile: Colombia and Ecuador demand profiles were estimated from Peru’s daily demand, Venezuela and Guyana from Brazil’s (North), Chile from Argentina’s and Paraguay from Brazil’s (Southeast).

3.7.2 Time zones

The countries were modelled in three time zones for an accurate representation of synergies related to distinct load curves and renewable generation. Brazil Southeast time was set as the reference, since it represents the main load region of the continent (EPE, 2014b). Thus, the first time zone comprises Argentina, Brazil (Southeast, Northeast and South regions) and Uruguay; the second one Bolivia, Brazil (North), Chile, Guyana, Paraguay and Venezuela; and the third Colombia, Ecuador and Peru.

3.7.3 Population

The population data and their future trends for each country were obtained from the Population Reference Bureau (PRB, 2013).

3.7.4 Technology performance

Appendix D provides an overview of the modelled technologies and their changing features over time, such as capacity factors, expected life times, efficiencies and cost data.

3.7.5 Transmission and distribution losses

The technical and non-technical losses in transmission and distribution networks reveal strong differences between countries, the lowest level being Chile (8.6%) and the highest Venezuela (32.3%) (CIER, 2013; MPPEE, 2014). Chilean national grid does not rely on high voltage long distance transmission lines as its generation mix includes high shares of thermal power, while Venezuela uses them extensively because it depends on hydro electricity produced far away in the Southeast to supply load centres in the Northern regions. The level of non-technical losses is mainly linked to stolen electricity from the grid, a big problem in Venezuela as well as in Brazil, where total losses reach 15.9% (EPE, 2014a). SAMBA scenarios consider decreasing transmission and distribution losses, so that in the long-term, they are expected to reach the level of developed countries — between 6% and 8% (IEA, 2012), depending on the presence of long distance high voltage transmission lines.

3.7.6 Costs

The following costs were considered: Investment cost, expressed in US$ per kW installed; fixed operation and maintenance costs (O&M), expressed in US$ per kW installed; variable operation and maintenance costs (O&M), expressed in US$/GJ; and fuel costs, expressed in US$ per unit. Domestic fuel prices were used when available in national reports, otherwise international prices were employed. Further, it is assumed that government subsidies affect long-term energy prices causing them to converge by 2058 towards international prices used by the WEO Reference Trade scenario IEA WEO (2014). Appendix D presents cost data for SAMBA scenarios.

3.7.7 Hydro capacity expansion and reservoirs

Considering the total hydro potential as presented in Table 7, a maximum installed capacity investment per year of up to 1 GW was assumed for Argentina, Bolivia, Brazil (Southeast and South), Chile, Colombia, Ecuador, Peru and Venezuela in the RTS. The maximum annual investment in the Northern subsystem of Brazil was set to 2 GW, due to its larger potential. For Paraguay, Uruguay and Brazil’s Northeast it was assumed the hydro potential was already totally exploited. In ITS, the strategic hydro projects (Table 4) were added and the maximum annual installed capacity investment was the same of RTS. As for the ATS, the maximum capacity expansion in hydro plants in Brazil was set at a lower level of up to 200 MW per year in the Northern subsystem, 100 MW in the subsystems of the South and Southeast and no hydro expansion in Brazil’s Northeast. Despite the large hydro potential in Brazil, there is an increasing resistance to build more dams in the Amazon, where the remaining potential is located, due to concerns over the environmental and social sustainability of such projects. Tundisi *et al.* (2014) discuss the impacts of building more dams in the Amazon basin and Santos and Legey (2013) presented *“a model for long-term electricity expansion planning with endogenous environmental costs”* and concluded that there is *"a reduction in the total cost of the expansion when previous environmental valuation studies where considered in the modelling of power plant technologies".*

The storage capacity of hydro reservoirs plays an important role in the Brazilian and Venezuelan power systems. In 2012, the water storage capacity of hydro reservoirs in Brazil could supply the average monthly national electricity consumption for more than four months without any additional inflow (EPE, 2014a; ONS, 2015b) and in Venezuela for more than five months (figure estimated from MPPEE, 2014). The storage capacity in SAMBA scenarios is measured in terms of the total equivalent energy of an aggregated reservoir, for Venezuela and for each of the four Brazilian sub-regions (Table 8).

Table 8 - Reservoir capacity
Source: based on (ONS, 2015b; MPPEE, 2014)

Country	Storage Capacity Maximum (PJ)	Storage Capacity Start of 2013 (PJ)
Brazil Southeast	540	143
Brazil Northeast	139	33
Brazil South	53	17
Brazil North	38	14
Venezuela[a]	144	72

[a] It was considered 50% of maximum capacity available in 2013

3.7.8 Wind resource for generating electricity

The on-shore wind potential of the continent has been estimated by several studies through distinct methodologies (Camargo Schubert *et al.*, 2001; MEN, 2008; Dicco, 2012; Ferreno, 2013; MEER, 2013; Santana *et al.* 2014; Longatt *et al.* 2014; Mattar *et al.*, 2014). The identified potential are: Brazil, 143 GW; Chile, 40 GW; Uruguay, 30 GW; Peru, 22 GW; and Ecuador, 1.6 GW. Some of these estimates were made more than ten years ago and should be updated to reflect technological developments. In Argentina, there have been many rumours of considerable wind potential, although no official estimate has been published. The lack of data is even worse concerning the off-shore wind potential of the continent.

Therefore, this study did not consider a maximum value for the exploitation of wind potential, but rather a constraint on the maximum annual investment in wind generator capacity. These constraints follow the pattern defined by LU *et al.* (2009), for both on-shore and off-shore wind generation, i.e., countries with annual potentials of more than 500 TWh (on-shore) and 30 TWh (off-shore) have a 1GW/year capacity addition limit, while countries with smaller annual potentials have a limit of 100 MW. The maximum annual investment in Argentina was set to 2 GW, due to the impressive (although unofficial) potentials, reaching 42.000 TWh (on-shore) and 5.000 TWh (off-shore).

3.7.9 Solar resource for generating electricity

Some studies estimate the solar potential in Chile (Santana *et al.*, 2014) and Brazil (Pereira *et al.*, 2006), and field reports have evaluated the environmental and economic feasibility of large centralized solar generation (EPE, 2012). Trieb *et al.* (2009) used a geographic information system (GIS) to assess the feasibility of solar power plants combining solar resource data with data for land use, topography, hydrology, geomorphology, infrastructure, and protected areas, to exclude sites that have not technical potential for building solar plants. Argentina, Bolivia, Brazil, Chile and Peru exhibit areas for large-scale electricity production using Concentrated Solar Power (CSP) plants, with an average annual irradiation higher than 2.000 kWh per square meter. For these countries then a maximum installed capacity investment per year of up to 1 GW for CSP was assumed, while Colombia and Venezuela who have areas of average annual irradiation (between 1.500 kWh and 2.000 kWh per square meter), the maximum capacity investment per year was limited to 100 MW. The same assumptions were applied to investments in large-scale solar photovoltaic plants.

As for the ATS, distributed photovoltaic was considered only in the electricity supply mix of Brazil to assess the impact of the penetration of this technology in 10% of households total by 2058. The country has recently introduced new regulations to incentivise investments in distributed generation (ANEEL, 2012; ANEEL, 2015b). It was assumed that each household is capable of generating its equivalent annual electricity demand. Besides, the average annual household electricity consumption increases from 2.056 kWh in 2013 to 4.000 kWh by 2058, a feature similar to the annual electricity consumption of households of developed countries in 2013, such as Greece (3.758 kWh), Portugal (3.545 kWh) and Spain (3.944 kWh) (WEC, 2015). The capacity factors for photovoltaics distributed were based on the solar resources availability of important capital cities in the four Brazilian power subsystems as presented in Table 9.

Table 9 - Distributed photovoltaic generation in Brazil
Source: based on (IBGE; 2015; WEC, 2015; Portal Solar, 2017)

Brazilian Power Subsystem	**Households (Million)**			**Solar Resource Base (City - State)**	**Capacity Factor**
	Total 2013	**Total 2058**	**10% with PV 2058**		
North	4.69	5.63	0.56	Belém - Pará	0.34
Northeast	16.40	19.72	1.97	Salvador - Bahia	0.37
South	9.66	11.60	1.16	Porto Alegre - Rio Grande do Sul	0.32
Southeast	32.15	38.65	3.86	São Paulo - São Paulo	0.27
Brazil	62.90	75.60	7.56		

3.7.10 Biomass for generating electricity

To avoid discussions related the competition between food and biofuels for land and water, it was assumed that only sugarcane was used for electricity generation. Indeed, bioelectricity in the continent is mostly produced from the incineration of sugarcane bagasse (first generation biofuel). In 2013, it represented 7% (42 TWh) of the total Brazilian electricity supply (EPE, 2014a). The historical production of bagasse in each country was identified (UN, 2015) and projected throughout the study horizon at an annual increase rate of 2%. The amount of sugarcane destined to electricity generation was assumed to be up to 25% of the total annual production, and a further 25% could be used to produce lignocellulosic biogas (second generation) to fuel thermal plants after 2020. EPE (2014b) estimates the electricity generation potential from bagasse incineration plants in Brazil in 2013 of up to 5.6 GWyr and projects a potential of 7.7 GWyr by 2023. In order to assess the impacts of such alternative generation technology it was assumed further in ATS that in Brazil the long-term (by 2058) investment cost of new biogas power plants (US$ 2.449/kW, in 2013) will converge to the investment cost of bagasse incineration plants in 2013 (US$ 1.905/kW).

3.7.11 Fossil fuels for generating electricity

The availability of natural gas for electricity generation was restricted in SAMBA scenarios. Producing countries cannot use more than 50% of the extracted resource for use in the power sector. For import countries, this 50% constraint applies to the total imported fuel. Future national productions are based on Hubbert curve methodology estimates using US EIA (2015) data. Further, shale gas production is expected to develop only in Argentina and Brazil due to their large reserves and land availability. In the SAMBA scenarios, total coal supply availability for electricity generation, on a per country basis, was set using the maximum dispatch of existing thermal plants, with an annual increment equivalent to the input of a 1 GW plant dispatched at full capacity.

New nuclear plants are only possible in Brazil and Argentina. Other South American countries do not have access to nuclear power technology and the SAMBA scenarios assume that this situation will remain. As the power sector does not consume crude oil but rather uses refined products (mainly diesel oil and fuel oil), these fuels' availability for electricity generation was limited to historical refining facilities and its evolution in each country (US EIA, 2015; UN, 2015).

3.7.12 Reserve Margin

The reserve margin is a measure of the power system reliability and is defined as the difference between the effective installed capacity and the system peak load, expressed in percentage value (Bautista, 2012). A power system with a high share of thermal generation usually works with 15-18% reserve margin (Rochin, 2004), mostly because the generation is not strongly affected by seasonality of energy sources. However, the reserve margin in South American countries varies from 30% to 40% (CIER, 2013) due to the large presence of hydroelectric, which is characterized by dry and wet seasons.

In this study, a 15% reserve margin was assigned to SAMBA scenarios; Renewable generation does not supply reserve margin, except large hydro, which is dispatchable. Hydro contribution was limited to up the capacity factor observed in each country during the month of highest demand, so that supply is not overestimated. International transmission lines, non-associated to binational hydropower, can only contribute to the reserve margin with 50% of their installed capacity.

3.7.13 Medium term expansion national plans

The expansion of installed capacity in the medium-term (2013-2018) corresponds exactly to the new power plants projects scheduled in government plans of the following countries: Bolivia (AE, 2012), Brazil (EPE, 2014b), Colombia (UPME, 2013), Ecuador (MEER, 2012), Guyana (GLP, 2012) Peru (MEM, 2014) and Venezuela (MPPEE, 2013b). For Argentina, Chile, Paraguay and Uruguay the expansion is based on PLATTS (2015). Results for system expansion from 2019 onwards are less constrained and relate directly to the OSeMOSYS SAMBA optimization process.

3.7.14 Carbon Emissions

Based on electricity production in the continent from 2011 to 2013, the average carbon dioxide emissions for each country was estimated by applying carbon intensity index values (US EPA, 2015) to fossil fuelled power generation. Then, a 34% reduction, by 2058, in the overall electricity's carbon intensity was imposed in the SAMBA scenarios, following results presented in IEA WEO (2014) for non-developed countries.

3.8 Results

Results obtained for the three scenarios are presented for the years 2013, 2018, 2038 and 2058. The initial years (2013-2018) were modelled according to short-term national plans and setting special constraints on the OSeMOSYS SAMBA optimization process. In order to have a comprehensive view of the impacts of the Brazilian policies, results for Brazil are compared to those of the other South American countries in aggregated form.

3.8.1 Generating Capacity

As compared to the RTS (Reference Trade) scenario, the strategic large hydro projects financed by Brazil under the ITS (Integrated Trade) scenario reduce the need for new capacity in Brazil by 23 GW in 2058, while increasing the generating capacity of other South America countries by 5 GW. As for ATS (Alternative Trade), the need in Brazil for new installed capacity increases by 11 GW by 2058 when compared to RTS, while increasing the generating capacity of other South America countries by 44 GW. Thus, the results indicate that the less integrated are the power systems, the bigger will be the need for new installed capacity.

The installed capacity in Brazil is expected to increase from 145 GW in 2018 to 350 GW (RTS), 327 GW (ITS) and 361 GW (ATS) by 2058. Brazil remains largely dependent on hydro generation: national capacity increases from 100 GW in 2018 to 131 GW (RTS) and 132 GW (ITS) in 2058. However, in ATS the hydro installed capacity in Brazil presents a lower expansion (111 GW), accounting for 30% of total installed capacity in 2058. Appendix E presents detailed data for installed capacity for SAMBA scenarios. The strategic projects abroad would displace investments in new NGCC plants, and reduce the rate of new capacity installations of renewables such as on-shore wind, concentrated solar and bagasse incineration plants, which are all intermittent generation technologies. On-shore wind expansion however is very similar in SAMBA scenarios reaching 53 GW (RTS), 52 GW (ITS) and 53 GW (ATS). Similarly, concentrated solar capacity in the northeast subsystem of Brazil increases significantly reaching 30 GW (RTS), 27 GW (ITS) and 28 GW (ATS). The policy of increasing the penetration of distributed photovoltaic in 10% of the households in Brazil by 2058, as modelled in ATS, results in an installed capacity of 7 GW by 2038 and 23 GW by 2058. The installed capacity of pulverized coal power increases from 3 GW in 2018 to 50 GW (RTS), 55 GW (ITS) and 39 GW (ATS)[9].

The other countries of South America present a great expansion of on-shore wind capacity, from 1.1 GW in 2018 to 83 GW (RTS and ITS) and 101 GW (ATS) in 2058. It also highlights the expansion of geothermal capacity in the Andean countries from 0.2 GW in 2018 to 11 GW in 2058 in all SAMBA scenarios. The hydroelectric capacity has the largest absolute increase from 72 GW in 2018 to 189 GW (RTS), 190 GW (ITS) and 167 GW (ATS) in 2058, not taking into account the new strategic large hydro's capacities. In RTS and ITS the investment mix in new capacity is mostly based on large hydropower, on-shore wind, biomass incineration, geothermal and pulverized coal. As for ATS, the new capacity mix is more diversified in 2058, especially due to distributed photovoltaics (23 GW), biogas power (22 GW) and NGCC plants (32 GW), the latter supplying the base load as the hydro presents a lower expansion.

3.8.2 Electricity Generation Mix

The imports from strategic hydro projects in ITS reduces Brazilian production up to 71 TWh, when comparing to the RTS, mostly from the projected NGCC, bagasse incineration and on-shore wind plants. In ATS, Brazilian electricity generation drops only 7 TWh by 2058, when compared to RTS, and relies on large hydro, biomass

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[9] The reason for this increase can be explained by the low cost of national coal and by the fact that the model did not include a carbon tax. In addition to this, the Brazilian South subsystem does not have many alternatives for increasing stable power generation, such as natural gas, leading OSeMOSYS SAMBA to choose higher coal generation capacity to meet demand.

incineration, wind on-shore, pulverized coal and NGCC plants. In ITS, the production from NGCC, geothermal, concentrated solar and on-shore wind drops in South America, when comparing to RTS, as the exports from hydro increases, thus reducing the generation mix diversity in the continent. Appendix E details the results obtained for the three SAMBA scenarios.

By 2058, hydropower predominates in almost all countries, accounting for 55% (RTS), 58% (ITS) and 45% (ATS) of total electricity generation in South America. In Brazil, hydroelectricity supply represents 46% (RTS), 54% (ITS) and drops to 39% of power generation (ATS). The dominance of hydro power is linked to the exploitation of the continent’s significant potential. Non-hydro Renewable electricity generation also has a strong expansion in the SAMBA scenarios and is mostly related to on-shore wind, solar thermal, bagasse incineration and geothermal power. In all three scenarios the nuclear generation is not competitive, indicating perhaps that the present nuclear generation programs in Brazil and Argentina were political decisions. Similarly, clean coal generation is not cost competitive due to the absence of a carbon tax policy in the South America power sector, which leads to a significant increase in generation from pulverized coal plants.

3.8.3 Reservoir Storage Capacity

Figures 3 and 4 illustrate the amount of stored equivalent electricity in major reservoirs in Brazil and Venezuela, in ITS and ATS respectively. In Brazil the storage capacity is expected to decline relative to total installed capacity by 2025, which means less backup power availability. The three scenarios have equivalent storage patterns, remaining at lower levels from 2025 up to 2045. Then, the increased generation from pulverized coal and NGCC plants would allow for a recovery on the reservoirs levels, in spite of increasing wind on-shore and large CSP penetration. In Venezuela, all SAMBA scenarios indicate the loss of hydro storage capacity from 2040 onwards, because the added new hydro plants are of the run-of-river type. Further developments on hydro modelling in SAMBA will be subject of future studies.

Figure 3 - Brazil’s hydro reservoir storage – Integration Trade SAMBA
Note: Brazilian system is represented by equivalent reservoirs in its four subsystems.

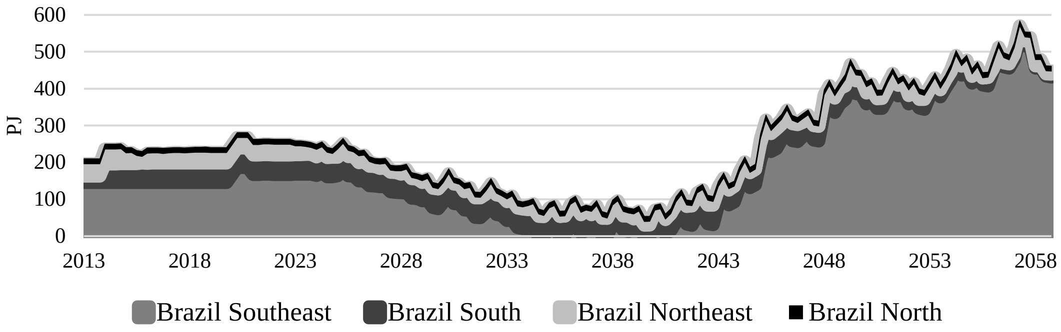
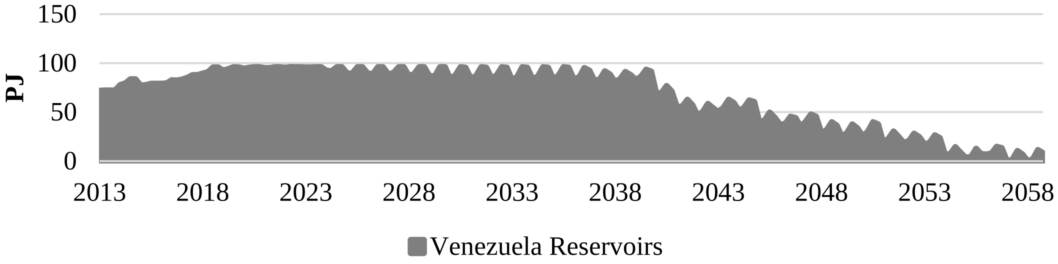


Figure 4 - Venezuela’s hydro reservoir storage – Alternative Trade SAMBA



3.8.4 Carbon Emissions

Despite a 34% reduction in the carbon electricity intensity by 2058 as compared to 2013, the total power sector carbon emissions increase from 167 million tons of CO2 in 2013 up to 333 million tons by 2058, in SAMBA scenarios. This is a consequence of the significant increase in generation caused by the greater access to electricity by the continent’s entire population, and the larger participation pulverized coal power in the generation mix. To deal with this, environmental constraints could be added to the model in order to represent political decisions related, for example, to the commitments made at the 2015 United Nations Climate Change Conference (21st Conference of the Parties).

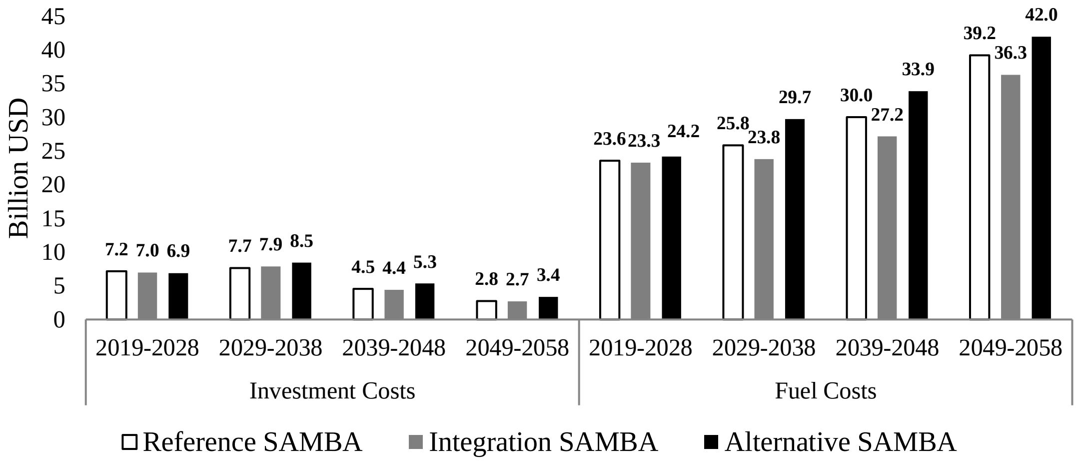
3.8.5 Financial Requirements

As shown in Figure 5, investment levels are similar in SAMBA scenarios, with fuel costs decreasing in ITS, as trade and participation of large hydro and wind generation increase. In ATS fuel costs increase due to the higher consumption of NGCC plants and low hydro expansion. In the 2019-2058 time period, the system’s total annual cost savings in ITS would range from 0.3 to 3 billion USD. On the other hand, the average annual costs in ATS would increase in the range of 0.6 to 2.8 billion USD as compared to RTS.

Brazil is the largest economy on the continent and has a higher capability of funding capital-intensive projects, such as large hydropower plants and transmission lines. Countries with large hydro potential but limited financial capacity, such as Bolivia and Guyana, could improve their power infrastructure through trade agreements with Brazil, while increasing their national budgets thanks to electricity trade and reduced fossil fuel spending. From the Brazilian perspective, the power systems integration as modelled in the ITS scenario helps to maintain operational costs and reliance on traded power low.

On the other hand, the ATS indicates higher investment and operational costs. The former as a consequence of higher penetration of other renewables (non-hydro) technologies, such as photovoltaic distributed, and the latter due to higher fuel spending as the NGCC plants become an important supply source.

Figure 5 - Total investment cost and fuel costs comparison in SAMBA scenarios



3.9 Game Theory Approach applied to SAMBA scenarios

In this section, the results related to cross-border electricity trade potential in SAMBA scenarios are presented and then assessed using a cooperative games approach, notably the Shapley Value concept.

3.9.1 Cross-Border Electricity Trade

In the RTS, it is interesting to note that Paraguay is the major exporter of electricity in the continent and particularly important to Brazil (914 TWh) and Argentina (173 TWh), as Table 10 shows, although the Paraguayan annual exports to Brazil and Argentina decrease significantly from 44 TWh in 2013 to 6 TWh in 2058. In the ITS, Peru, Guyana and Bolivia use the Brazilian investments in large hydropower and associated transmission lines to become electricity exporters with estimated potentials of up to 1336 TWh, 757 TWh and 294 TWh, respectively, by 2058 (Table 11). In other words, the total trade potential of the continent could increase by more than 200%. Paraguay electricity exports decrease by 52 TWh as the cross-border trade increases overall, although the country remains an important exporter to Brazil and Argentina. Finally, despite increasing net imports, Brazil's power dependency in the ITS would represent only 5% of its total supply in 2058, a lower level than in 2013 (7%). As for ATS, the potential international trade (1.234 TWh) would be similar to the one indicated by RTS, because Brazil would consider alternative internal supply options, rather than a strong expansion of electricity imports (Table 12).

Table 10 - Total Electricity Trade (2013-2058) in Reference Trade SAMBA

Country		**Electricity Exports (TWh)**											
		Argentina	**Bolivia**	**Brazil**	**Chile**	**Colombia**	**Ecuador**	**Peru**	**Paraguay**	**Uruguay**	**Venezuela**	**Guyana**	**Total**
Electricity Imports (TWh)	**Argentina**		0	1	4				173	0			**178**
	Bolivia	0		0	0			0	0				**0**
	Brazil	41	0			0		0	914	7	8	0	**969**
	Chile	5	0					0					**5**
	Colombia			0			5	0			3		**8**
	Ecuador					4		3					**8**
	Peru		0	0	0	0	1						**1**
	Paraguay	0	0	0									**0**
	Uruguay	14		7									**20**
	Venezuela			2		2						0	**3.6**
	Guyana			0							0		**0**
	Total	**59**	**0**	**9**	**4**	**7**	**5**	**3**	**1088**	**7**	**11**	**0**	**1192**

Table 11 - Total Electricity Trade (2013-2058) in Integration Trade SAMBA

Country		**Electricity Exports (TWh)**											
		Argentina	**Bolivia**	**Brazil**	**Chile**	**Colombia**	**Ecuador**	**Peru**	**Paraguay**	**Uruguay**	**Venezuela**	**Guyana**	**Total**
Electricity Imports (TWh)	**Argentina**		0	2	4				171	0			**177**
	Bolivia	0		0	0			0	0				**0**
	Brazil	32	294			0		1333	865	6	12	757	**3299**
	Chile	5	0					0					**5**
	Colombia			0			5	0			3		**8**
	Ecuador					5		3					**8**
	Peru		0	0	0	0	1						**1**
	Paraguay	0	0	0									**0**
	Uruguay	11		22									**33**
	Venezuela			116		2						0	**117**
	Guyana			0							0		**0**
	Total	**47**	**294**	**139**	**4**	**7**	**5**	**1336**	**1036**	**6**	**15**	**757**	**3647**

Table 12 - Total Electricity Trade (2013-2058) in Alternative Trade SAMBA

Country		Electricity Exports (TWh)											
		Argentina	**Bolivia**	**Brazil**	**Chile**	**Colombia**	**Ecuador**	**Peru**	**Paraguay**	**Uruguay**	**Venezuela**	**Guyana**	**Total**
Electricity Imports (TWh)	**Argentina**		0	0	4				201	0	0		**206**
	Bolivia	0		0	0			0	0				**0**
	Brazil	42	0			0		0	909	6	7	0	**964**
	Chile	5	0					0			0		**5**
	Colombia			0			5	0			4		**9**
	Ecuador					7		4					**10**
	Peru		0	0	0	0	1						**1**
	Paraguay	0	0	0									**0**
	Uruguay	17		20									**36**
	Venezuela			0		2						0	**2**
	Guyana			0							0		**0**
	Total	**64**	**0**	**20**	**4**	**9**	**6**	**4**	**1110**	**6**	**11**	**0**	**1234**

3.9.2 Cooperative Games and Shapley Value

In cooperative games, the Shapley value concept draws from the idea of a fair distribution of payoffs. It can be obtained by calculating the expected contribution of each player to the total payoff of the grand coalition, which is formed by all players participating in the game. It's important to highlight that all coalitions must be equally probable, with players joining in randomly. The calculated value represents a player's bargaining power, and since it represents the player's average contribution to the coalition, it is the fair amount the player should receive from the profit sharing among players (Naveiro *et al.*, 2009).

Osborne and Rubinstein (1994), Kleinberg and Weiss (1986) present a full explanation of the axioms needed to compute the Shapley Value. Medina (2012) and Straffin (1993) instead briefly describe these axioms as follows:

- Efficiency: The exact amount of resources available to the grand coalition is distributed among the players. The sum of each players' Shapley Value is equal to the value of the grand coalition;
- Symmetry: two players are said to be symmetric with respect to the game if they make the same marginal contribution to any coalition. The symmetry axiom requires symmetric players to be paid equal shares; and
- Additivity: if two coalition games are combined, then the distributed payoffs should correspond to the sum of the payoff in each coalition; and
- Null player: if there is a player who adds no value to any coalition, i.e. a so-called dummy player, then its Shapley value is zero. Furthermore, adding a dummy player to a game does not change the Shapley Value of other players in the game.

Although there are several methods (Kleinberg *et al.*, 1985; Bilbao *et al.*, 2000; Ieong *et al.*, 2005; Conitzer *et al.*, 2004) for calculating the Shapley Value of a player on a game of n players, we mention here only two of them. The first is based on a table representation of all possible orders a player might be included in a particular coalition. This becomes rapidly infeasible for larger games since the number of possible orders of participation is n! thus growing very rapidly as n increases. For the SAMBA scenarios, where 11 countries represent the players, almost 40 million coalitions are possible.

The second method, presented in Straffin (1993) and described in detail ahead, was the one chosen for the present analysis. In this method, instead of looking at the Shapley value for all players, we focus on a particular player i and compute how frequently and how much this player contributes to the formation of the grand coalition. Thus, when player i is added to coalition S ($i \in$ S) in the process of creating the grand coalition, its contribution depends on the players who already are in coalition S, of size s. The value (v) of player i contribution is $v(S) - v(S - i)$, which occurs in those entrance orders for which i is preceded by the $s - 1$ other players in S, and followed by the $n - s$ players still not in S. Since this happens $(s - 1)!\,(n - s)!$ times, it is possible to write the Shapley value for player i as

$$\varphi_i = \frac{1}{n!}\sum_{i \in S}(s-1)!\,(n-s)!\,[v(S) - v(S-i)] \qquad (where\ s\ is\ the\ size\ of\ S)$$

Thus, instead of all the $n!$ computations necessary to find the Shapley value for all players i (i = 1,…, n), for a particular player i only a summation over the 2^{n-1} coalitions S which contain i is needed.

In the SAMBA scenarios, where 11 countries (players) participate, the contribution of a given country had to be calculated for each of the 1024 (or 2^{10}) possible coalitions it could join, so as to identify its bargaining power. This calculation was carried out through an algorithm developed in Scilab (2016) available in Appendix B.

The bargaining power of each country can be interpreted as the importance of that country to a group of countries, as for example, how Brazil might influence its neighbours by building strategic hydro projects in order to boost cross-border trade. The grand coalition payoff is the sum of the electricity traded across all international transmission lines in the continent, which is shared fairly among countries, as a function of each country’s contribution. Hence, the greater a country’s contribution to cross-border trade, the higher its bargaining power. The Shapley value approach applied to long-term power integration planning might therefore stimulate countries to cooperate, thus increasing energy security and optimizing the use of energy resources.

3.9.3 Theoretical Bargaining Power

As shown in Table 13, despite receiving 91% of total cross-border trade profit in the RTS, Paraguay’s bargaining power is only equivalent to 544 TWh – or 46% of total trade – since the rest is shared with Brazil as the only possible importer under the Itaipu binational dam treaty. Argentina also has a significant bargaining power – equivalent to 10% of total trade – which is related to the Yacireta binational dam built with Paraguay. The other cross-border connexions would not play important roles on the continent’s total international trade in the RTS.

Under the ITS, Brazilian investments abroad would change cross-border electricity trade significantly; thereby affecting each country’s theoretical bargaining power as well. Brazil’s contribution to international trade in the region would reach 1717 TWh, which means an increase of its bargaining power to 47%. Peru and Guyana would also have large export potential, which gives them bargaining powers of 18% and 10%, respectively. On the other hand, Paraguay and Argentina’s bargaining power would drop significantly to 14% and 3%, respectively, as Brazil would have more supply options. Although facing a reduced bargaining power, Paraguay would still receive 28% of the total cross-border trade profit, which is lower than Peru (37%) but higher than Guyana (21%).

For ATS, the bargaining powers of the countries are quite similar to those found in RTS, with only a slight increase in international trade (+3.5%), as Brazil seeks to expand its electricity supply by making use of national alternative sources such as distributed photovoltaics, biogas power plants and NGCC, to substitute for the absence of large hydropower to fulfil base load needs.

Table 13 - Theoretical Bargaining Power

Scenario	Countries	Total Potential Trade (TWh)	Exports (TWh)	% of Cross-border Trade Profit	Shapley Value (TWh equivalent)	Theoretical Bargaining Power
Reference Trade SAMBA	Argentina	1191.2	58.9	4.9%	118.3	10%
	Bolivia		0.0	0.0%	0.0	0%
	Brazil		8.9	0.7%	488.6	41%
	Chile		3.7	0.3%	4.1	0%
	Colombia		6.6	0.6%	7.2	1%
	Ecuador		5.5	0.5%	6.6	1%
	Guyana		3.1	0.3%	0.0	0%
	Paraguay		1087.0	91.2%	543.6	46%
	Peru		6.6	0.6%	2.1	0%
	Uruguay		10.9	0.9%	13.6	1%
	Venezuela		0.0	0.0%	7.1	1%
Integration Trade SAMBA	Argentina	3646.9	47.4	1.3%	113.5	3%
	Bolivia		294.0	8.1%	144.7	4%
	Brazil		139.3	3.8%	1716.8	47%
	Chile		4.3	0.1%	4.5	0%
	Colombia		6.9	0.2%	7.5	0%
	Ecuador		5.2	0.1%	6.5	0%
	Guyana		756.9	20.8%	379.5	10%
	Paraguay		1035.8	28.4%	519.0	14%
	Peru		1335.8	36.6%	669.0	18%
	Uruguay		5.8	0.2%	19.5	1%
	Venezuela		15.4	0.4%	66.4	2%
Alternative Trade SAMBA	Argentina	1233.9	63.6	5.2%	134.6	11%
	Bolivia		0.0	0.0%	0.0	0%
	Brazil		19.9	1.6%	492.2	40%
	Chile		4.2	0.3%	4.6	0%
	Colombia		9.1	0.7%	9.1	1%
	Ecuador		5.8	0.5%	8.1	1%
	Guyana		0.0	0.0%	0.0	0%
	Paraguay		1110.3	90.0%	555.2	45%
	Peru		4.0	0.3%	2.1	0%
	Uruguay		6.0	0.5%	21.4	2%
	Venezuela		11.0	0.9%	6.7	1%

This comprehensive perspective could assist Brazilian and Paraguayan policy makers to reach a fair energy trade agreement during the renegotiation of Itaipu binational treaty, which will expire in 2023. This study does not however cover all integration possibilities. Indeed, by moving away from a focus on Brazil, it would be interesting to see how considering Paraguayan and other countries' perspectives would help to enhance continental cooperation in long-term power expansion plans. But again, this is beyond the scope of the present paper.

3.10 Conclusion and Policy Implications

The extensive bibliographical revision to identify power sector features of the eleven countries modelled in the SAMBA scenarios allowed for a better representation of the long-term power integration process. Despite the limitations akin to large scale models, OSeMOSYS SAMBA might provide important information for policy makers, especially those related to an accurate representation of renewable energy technologies, which participation is ever increasing.

The South American power sector is highly dependent on hydro generation, and the modelling of reservoirs storage capacity in Brazil and Venezuela highlights their increasing variability along the years as the generation mix diversifies. A more extensive and accurate sensitivity analysis of the contribution of hydro power to reserve margin levels could shed light on how the reservoirs are affected as cross-border trade increases.

The Brazilian perspective of power integration based on funding strategic hydropower projects abroad would ensure the availability of large amounts of electricity imported mostly from Peru and Guyana. The SAMBA scenario comparison indicates a reduction of up to 23 GW in Brazilian installed capacity expansion and an addition of 5 GW in the installed capacity of the other countries in South America. The generation remains based on hydro because of its potential largely unexplored, although on-shore wind, pulverized coal and concentrated solar would become important sources by 2058.

Concerns over the environmental and social sustainability of large hydropower are key issues but fall beyond the scope of the present paper. Some of the strategic hydro projects abroad considered by Brazil are located in the Amazon forest and the sustainability of such dams is questionable. As Tundisi *et al.* (2014) highlights *"the construction of hydroelectric reservoirs to support economic development of Brazil and other countries that share the Amazon basin will interfere with the ecological dynamics of the ecosystem changing the hydrological, hydrosocial and fundamental processes".* Since most countries in the continent are young and fragile democracies, hydro projects in the Amazon may also violate human rights since minority voices such as those of indigenous people and communities affected by dams are not properly considered by the governments.

The Brazilian perspective of power systems integration — as modelled by the ITS — leads to the maintenance of a low operational cost of its power mix and low external dependence. The total trade potential in the continent could increase by more than 200%, as compared to the RTS. Countries with large hydro potential but with limited financial capacity, such as Bolivia and Guyana, could improve their power infrastructure through trade agreements with Brazil, while increasing national budgets thanks to the electricity trade and reduced fossil fuel spending. Furthermore, Peru would become the most important electricity exporter to Brazil as the country makes use of its hydro potential located in Peruvian Amazon.

On the other hand, if Brazil chooses to prioritise domestic electricity sources — as modelled in ATS — instead of focusing on power integration based on large hydropower production (abroad and in its territory), its international dependence would be almost nil, would have a more diversified generating mix, although with higher investment and operational costs. The bargaining power of the countries would be almost the same as the ones indicated by RTS.

The changes in the South America power sector presented here have considerable impacts on each country's theoretical bargaining power, as Brazil overpasses Paraguay as the most influent player, in spite of being the largest importer. The Shapley value approach for cooperative games applied to the SAMBA scenarios sheds light on the amount of electricity trade each country brings to the integration process, helping policy makers to reach the most suitable trade agreement associated to a bilateral relationship. Further developments in the methodology presented here may include the influence relation introduced by Isbell (1958), who compare the influence of voters in a simple game.

As a final word, it is worth highlighting that there are many difficulties related to the pricing of *ex ante* and *ex post* energy in international grid connections, since each country has its own system operator and national regulation. This imposes a huge barrier to the integration process, as pointed out by Hira and Amaya (2003). Hence, despite the trade potentials the move towards continental grid coordination in South America still remains an intention. Future research will focus on the regulatory aspects of cross-border electricity trade legislation, in order to enhance long-term power sector cooperation in the continent.

4 Segundo ensaio: Bolivian Electricity Export Potential and Bargaining Power: An OSeMOSYS SAMBA Approach[10]

4.1 Abstract

Bolivia has plenty of energy resources that can supply not only its own electricity demand but has also the potential to export surplus production to its neighbors in South America. This study presents a comparative analysis of the electricity export potential of Bolivia, considering modelling results carried out by the Bolivian government and those from OSeMOSYS SAMBA - South America Model Base. Four scenarios were modelled from different conceptions of strategic large hydropower combinations. The scenarios comparison highlights the cross-border potential trade between Bolivia and neighboring countries, mainly Brazil. Using a Cooperative Games approach, through the calculation of the Shapley value, the bargaining power of Bolivia was identified, reaching its higher value in the scenario where El Bala and Cachuela Esperanza dams are present. The cooperative games approach provides a better understanding of electricity trade opportunities to support policy makers in international negotiations, thus considerably reducing incentives to non-cooperative actions.

4.2 Highlights

We model the long-term dynamics of power systems integration in South America.

Four scenarios simulate the cross-border electricity trade from a Bolivian perspective.

The Shapley value concept was used within a cooperative game theory approach.

We assess the Bolivia’s theoretical bargaining power on cross-border electricity trade.

The proposed methodology may support policy makers during international negotiations.

4.3 Keywords

Power systems integration; OSeMOSYS SAMBA; Cross-border electricity trade; Cooperative Games; Shapley value;

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[10] Artigo submetido à revista Energy Strategy Reviews em Setembro de 2016.

4.4 Introduction

South American countries present vast resources for generating electricity which could supply their national domestic demand and generate export surpluses. This study presents a model in which the power systems of ten countries – Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay and Venezuela – are represented as well as all existing grid interconnections between countries. Table 14 shows demographic and social-economic data of the South American countries studied.

Power integration on the continent is capable of improving the use of energy resources by exploring existing synergies in power production and different consumption patterns in each country. Power production in South America is mostly hydropower, which eases the penetration of other renewables generation technologies, since reservoirs' storage might provide backup production to address intermittent generation sources, such as wind farms and photovoltaic power plants. In addition, hydropower combined with natural gas fired power plants, can optimize electrical systems' power generation. Nevertheless, there are many barriers to increasing power integration, such as the lack of transmission infrastructure, different energy market regulations and the absence of financial resources (Hira and Amaya, 2003 and Rodrigues, 2012).

Table 14 - South America Outlook 2013
Source: Own elaboration, based on PRB (2013), CIER (2013) and World Bank (2015)

Country	Area (km^2)	GDP (USD Billion)	Population	GDP per capita (USD per capita)	Electricity Consumption[a] (TWh)	Electricity Consumption / population (kWh per Capita)
Argentina	2.780.400	583.1	41.3	14119	113.0	2735
Bolivia	1.098.581	33.0	11.0	3000	6.3	574
Brazil	8.515.767	1774.7	195.5	9078	464.1	2374
Chile	756.102	240.8	17.6	13682	66.8	3795
Colombia	1.141.748	292.1	48.0	6085	54.5	1134
Ecuador	276.841	100.2	15.8	6342	20.9	1324
Paraguay	406.75	27.1	6.8	3985	9.0	1324
Peru	1.285.216	189.1	30.5	6200	35.8	1174
Uruguay	181.034	53.4	3.4	15706	8.6	2516
Venezuela	916.445	371.3	29.7	12502	91.1	3067

[a] Gross production + imports exports transmission/distribution losses

Located in the Western-central South America, Bolivia is a landlocked country that shares borders with Brazil (North and East), Paraguay (Southeast), Argentina (South), Chile (Southwest) and Peru (Northwest). Its strategic location could make the country an important electricity exporter in the continent. The Bolivian government National Power Plan – Plan Eléctrico del Estado Plurinacional de Bolivia 2025 identified three strategic large hydropower, along with their electricity export potential: Cachuela Esperanza, with 990 MW installed capacity; El Bala, with 1.680 MW; and the Río Grande hydropower complex with 2.882 MW, representing total investments of up to USD 8.8 billion (MHE, 2014b). The national power plan highlights that additional studies must be carried out to estimate investments in long-distance transmission lines (between 1.500 – 2.500 km, approximately) so as to connect these strategic projects to their main load destinations abroad: Brazilian Southeast subsystem and Argentina (MHE, 2014b).

Bolivia's hydro potential is located in three major basins that sum up to 40 GW of installed capacity, or 173.000 GWh per year: the Amazon in the north; the highland enclosed in the center; and the La Plata in the south (OLADE, 2012 and MHE, 2014b). In 2014, the hydropower-installed capacity in Bolivia was 465 MW, which represents only 1% of its potential. Moreover, as Table 15 shows, its capacity mix in 2014 was largely based on natural gas plants (CIER, 2015).

Table 15 - Installed Capacity and Generating Mix in Bolivia in 2014
Source: Own elaboration, based on CIER (2015)

Power Plant Technology	Installed Capacity (MW)	Share	Production (GWh)	Share
Natural Gas Open Cycle	891	48%	4057	48%
Natural Gas Combined Cycle	194	10%	1356	16%
Diesel and Fuel Oil	285	15%	778	9%
Hydro	465	25%	2233	26%
Wind	3	0%	8	0%
Biomass	27	1%	76	1%
Total	**1865**	**100%**	**8508**	**100%**

According to the national power plan (MHE, 2014b), these strategic large hydropower projects present many advantages, such as the reduction of price volatility; an increase of cross-border electricity trade; and greater energy security. In addition, the electricity revenues would increase the national budget and support policies to promote Bolivia's development.

Table 16 presents the main electricity exporters and importers in South America. Brazil and Argentina are the major importers (76% and 22% of total imports respectively) notably from the binational hydro projects – Itaipu Dam (Brazil and Paraguay – 14 GW) and Yacireta Dam (Argentina and Paraguay – 3.1 GW). In spite of its strategic location, there are no reliable numbers on how much and to what extent Bolivia would export to its neighbors on the medium and long-terms, since they also have abundant energy resources for their own power system expansion (OLADE, 2012).

Moreover, other countries on the continent are expected to become major electricity exporters as well, notably Peru. Actually, Peru has made an agreement with Brazil to trade the electricity surplus from the Inambari dam (1.379 MW) located in the Peruvian Amazon and which is due to start production in 2019 (PLATTS, 2015).

Table 16 - Electricity imports and exports in South America in 2014
Source: based on CIER (2015)

International Trade (GWh)		Exports										Total Imports	Share
		Argentina	**Bolivia**	**Brazil**	**Chile**	**Colombia**	**Ecuador**	**Peru**	**Paraguay**	**Uruguay**	**Venezuela**		
Imports	**Argentina**	-	-	3	4	-	-	-	8461	1267	-	9735	22%
	Bolivia	-	-	-	-	-	-	-	-	-	-	0	0%
	Brazil	1	-	-	-	-	-	-	32939	-	839	33779	76%
	Chile	-	-	-	-	-	-	-	-	-	-	0	0%
	Colombia	-	-	-	-	-	20	-	-	-	-	20	0%
	Ecuador	-	-	-	-	718	-	13	-	-	-	731	2%
	Peru	-	-	-	-	-	-	-	-	-	-	0	0%
	Paraguay	-	-	-	-	-	-	-	-	-	-	0	0%
	Uruguay	-	-	-	-	-	-	-	-	-	-	0	0%
	Venezuela	-	-	-	-	28	-	-	-	-	-	28	0%
Total Exports		1	0	3	4	746	20	13	41400	1267	839	44293	
Share		0%	0%	0%	0%	2%	0%	0%	93%	3%	2%		

The unexploited large hydro potential of neighbouring countries is a subject of discussion among Brazilian power sector specialists, who seek to understand better the related social, environmental, technical and economic impacts of possible projects (Raineri *et al.* 2014; Castro, 2010). Complementarities between wet and dry seasons in different hydro basins could increase energy security, although long-term impacts and trade benefits are unknown (MME, 2006).

In Brazil, the remaining large hydro potential is in the Amazon region, but new projects have been criticized because of their environmental and social impacts. The Belo Monte dam is a prime example of the problems created by the population relocation and violence at workers' villages, besides the environmental impacts caused by the dam construction.

Under those circumstances, the Brazilian government is interested in funding strategic hydropower projects in neighbouring countries with large potential, so as to make possible the importation of large amounts of low cost electricity. It is worth to highlight the impacts of the economic crisis in Brazil on the weakening of electricity demand since 2015 (a decrease of 2.1% and 0.9%, respectively, in 2015 and 2016) (EPE, 2017). The short-term macroeconomic and political conditions in Brazil are as yet not favourable to funding hydro dams abroad. Thus, the assessment of such projects might be postponed even though they remain viable in the long-term.

This paper aims to discuss the Bolivia’s role as a major electricity exporter in South America, using a cooperative games approach with the application of the Shapley value concept. The objective is to shed light on the bargaining power of Bolivia in a possible cross-border electricity trade negotiation, under four different scenarios. This analysis shows how an asymmetrical bargaining power—and distortions of a country’s payoffs vis-à-vis their Shapley value—impacts the continent’s trade perspectives (Naveiro *et al.*, 2009). Along those lines, the proposed methodology may provide important information to support policy makers in international negotiations, thus considerably reducing incentives to non-cooperative actions.

The paper is structured in four sections besides this Introduction. Section 3.5 presents the applied methodology and the tools used to implement it, while section 3.6 presents the results obtained for the scenarios modelled. In the 3.7 section a cooperative game theory approach is used to identify the theoretical bargaining power of Bolivia and other countries in the region. Conclusions of this study as well as suggestions for future research are provided in section 3.8.

4.5 Methodology

Table 17 shows four scenarios for increasing the power integration in South America, considering the construction of the strategic large hydropower plants up to 2025, as planned by the Bolivian government (MHE, 2014b). The potential electricity trade is analysed under two different approches: the one presented by the Bolivian government using the Generation and Interconnection Capacity Expansion Planning Model – OPTGEN model in which no interactions with other countries are considered, and another using OSeMOSYS SAMBA – South America Model Base, developed built by the authors.

Table 17 - Strategic large hydro projects planned by the Bolivian government
Source: based on MHE (2014b)

Scenario	Strategic Large Hydro Projects	Total Capacity (MW)	Average Capacity Factors
I	Cachuela Esperanza (990 MW) and Río Grande Hydro Power Complex (2882 MW)	3872	0.32
II	Cachuela Esperanza (990 MW) and El Bala (1680 MW)	2670	0.42
III	Cachuela Esperanza (990 MW), El Bala (1680 MW) and Partialy Río Grande Hydro Power Complex (550 MW)	3220	0.44
IV	Río Grande Hydro Power Complex (2882 MW)	2882	0.24

The medium-term (2013-2025) power scenarios built by the Bolivian government used the computational tool called Generation and Interconnection Capacity Expansion

Planning Model – OPTGEN, for obtaining the least-cost expansion plan for an electricity and natural gas multi-region system. OPTGEN is an integrated expansion model formulated as a large scale mixed integer linear optimization problem, which is capable of modelling both continuous and integer decision variables under multiple scenarios and user provided expansion plans, besides other features (PSR, 2016).

The scenarios built in OPTGEN do not consider the medium-term power capacity expansion of Bolivia's neighbors, so that the potential cross-border trade is based on different assumptions of short and medium-term marginal power costs in Argentina, Brazil, Chile, Paraguay and Peru, as presented in Table 18.

Table 18 - Marginal Costs for producing electricity in Bolivia's neighbours
Source: based on MHE (2014b)

Country	Marginal Cost (USD/MWh)	
	2013	2017
Argentina	44	52
Brazil	55	82
Chile	80	80
Paraguay	40	40
Peru	35	47

The Open Source energy Modelling System – OSeMOSYS is an optimization software for long-term energy planning. The implementation of the South America power sector in OSeMOSYS was named SAMBA, an acronym for South America Model Base. The SAMBA version of the code as well as detailed methodological information is available in Appendix A and at www.osemosys.org.br (OSeMOSYS, 2015). The South America power sector was modelled through a quantitative approach which includes all existing grid interconnections between countries. The base year is 2013, with four scenarios built for the period 2013–2058[11].

Data was gathered from a great number of sources: monthly and annual reports of sectorial institutions; national expansion plans from energy ministries, state owned or private companies; and International organization reports. In addition, an extensive bibliographical search was carried out to identify power sector features of ten countries: Argentina (MPF, 2013; CNEA, 2015a; CNEA, 2015b; CAMMESA, 2015a; CAMMESA, 2015b), Bolivia (AE, 2012a; AE, 2012b; AE, 2013; MHE, 2014a; MHE, 2014b), Brazil (EPE, 2012; EPE, 2013; EPE, 2014a; EPE, 2014b; EPE, 2014c; EPE, 2015a; EPE, 2015b; ONS, 2014; ONS, 2015a; ONS, 2015b; MME, 2006; MME, 2014),

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[11] To avoid border effects, results and data for the last five years (2059-2063) were discarded.

Chile (CDEC SING, 2012; CDEC SIC, 2013; MEN, 2014; MEN, 2015); Colombia (MME, 2011; UPME, 2013; SIEL, 2015); Ecuador (MEER, 2012; CONELEC, 2013; ARCONEL, 2014a; ARCONEL, 2014b); Paraguay (ANDE, 2015; VMME, 2014; VMME, 2015); Peru (MEM, 2014a; MEM, 2014b; COES SINAC, 2013; COES SINAC, 2015); Uruguay (DNE, 2005; DNE, 2013; ADME, 2015a; ADME, 2015b) and Venezuela (CNG, 2008; MPPEE, 2013a; MPPEE, 2013b; MPPEE, 2014; CORPOELEC, 2015).

Additionally, international organization reports provided the following important data: Síntesis Informativa Energética de los países da CIER 2013 (CIER, 2013), Panorama General del Sector Eléctrico en América Latina y Caribe (OLADE, 2012), Apuntes Sobre la Integración Elétrica Regional y Propuestas para Avanzar (OLADE, 2013), Potencial de Recursos Energéticos y Minerales em América del Sur (UNASUR, 2013), Agenda de Proyectos Prioritarios de Integración (IIRSA, 2015), World Energy Outlook (WEO) 2014 (IEA WEO, 2014), Energy Technologies Perspectives (ETP) (IEA ETP, 2012; IEA ETP, 2014; IEA ETP, 2015), ETSAP Technology Brief (IEA ETSAP, 2010a; IEA ETSAP, 2010b; IEA ETSAP, 2010c; IEA ETSAP, 2010d; IEA ETSAP, 2010e; ETSAP, 2010f; IEA ETSAP, 2013a; IEA ETSAP, 2013b; IEA ETSAP, 2014), World Energy Perspective Cost of Energy Technologies (WEC, 2013) and World Bank (Word Bank, 2015). Finally, United States institutions were also an important data source (US EPA, 2014; USGS, 2006; US EIA, 2015).

OSeMOSYS SAMBA only considers the electricity supply from large power plants and does not take decentralized generation into account. Technology costs for generating and transmitting electricity were taken from the Energy Technology Systems Analysis Program (IEA ETSAP, 2014) and ETP reports (IEA ETP, 2012; IEA ETP, 2014; IEA ETP, 2015). The modelling considered aggregated groups of fifteen electricity generation technologies for each country[12] as well aggregated capacity for national transmission and distribution lines and international transmission lines. As for Bolivia, there is not operational international power connection with its neighbours. Associated transmission lines for the strategic large hydro projects and their equivalent installed capacity were modelled in SAMBA in order to meet national demand, while the surplus production exports were limited up to the new hydro installed capacity

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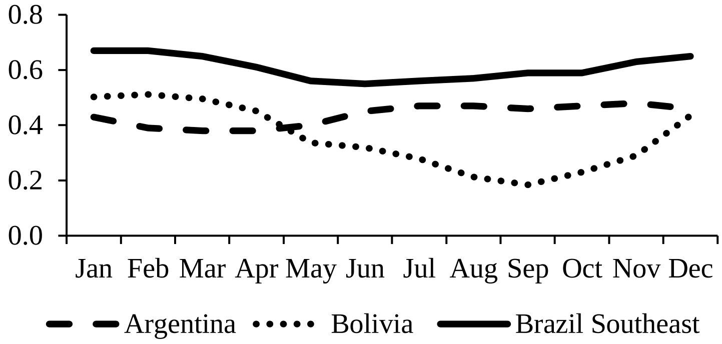
[12] The Brazilian power system was modelled with four subsystems (North, Northeast, South and Southeast) for a better representation of its continental dimension.

considered. Appendix D presents the generation input data used in the OSeMOSYS SAMBA scenarios.

Complementarities between wet and dry seasons in different hydro basins could increase energy security, although long-term impacts and trade benefits are unknown (MME, 2006). In SAMBA a typical year is represented by 48 characteristic time periods (12 months with early morning, morning, afternoon and night distinction for one type of day) per year. As variations of the capacity factor during the day were not considered, the modelling of hydro productions follow average monthly historical patterns. Figure 6 shows the capacity factors of hydro plants modelled for Bolivia, as well as for Argentina and Brazil (Southeast) the countries considered as potential importers.

Figure 6 - Capacity factors of hydro plants in OSeMOSYS SAMBA



Brazil (Southeast) and Bolivia have similar hydro production patterns, although the former presents a more constant production along the year due to reservoir storage. However, the backup generation provided by this storage will not be available in the near future, because due to environmental constraints, new hydro plants in Brazil are essentially of the run-of-the river type, which means less flexibility for hydroelectric generation (EPE, 2014b). In this context, Bolivian strategic hydro projects might become an important supplier to Brazil. A greater complementarity of hydro patterns exists between Argentina and Bolivia, although the potential electricity exports will depend also on Argentina's electricity needs.

It is worth to highlight, that the generation expansion as presented by Bolivian power plan (MHE, 2014) relies mostly on natural gas fired power plants. An estimate of the natural gas availability in Bolivia up to 2030 was presented by Chavez-Rodríguez *et al.* (2016) and one of the most important remarks was that *"Bolivia would possible require more than its current proven plus probable plus possible reserves"*. In 2013 the consumption from these plants (1 Million cubic meters per day) was equivalent to 41%

of natural gas national demand and it is expected to account for 25% of national consumption in 2025 (1,4 Million cubic meters per day).

The availability of natural gas for electricity generation in OSeMOSYS SAMBA scenarios was restricted according to national gas reserves in South America countries US EIA (2015). Producing countries cannot use more than 50% of the extracted resource for use in the power sector. For import countries, this 50% constraint applies to the total imported fuel. Future national productions are based on Hubbert curve methodology estimates using US EIA (2015) data. Further, shale gas production is expected to develop only in Argentina and Brazil due to their large unproved recoverable resources (802 and 245 Trillion cubic feet, respectively) and land availability. The natural gas exporting capacities from Bolivia to Argentina and to Brazil were set 8.2 and 32.8 Million cubic meters per day, respectively (CIER, 2015; OLADE, 2013).

4.6 Results

Due to the different time periods considered in the modelling—OPTGEN: 2013-2025; OSeMOSYS SAMBA: 2013-2058—, the comparison of results[13] for cross-border electricity trade from strategic large hydro projects planned by the Bolivian government are presented only for 2025 (Table 19), when all projects would reach their total installed capacity. In OSeMOSYS the first year of production is 2022, although with partially installed capacity.

Table 19 - Bolivia Potential Electricity Surplus for exporting in 2025

Scenario	**Strategic Large Hydro Projects**	**Cross-Border Potential Trade (TWh) - 2025**		
		OPTGEN	**OSEMOSYS SAMBA**	
I	Cachuela Esperanza (990 MW) and Río Grande Hydro Power Complex (2882 MW)	23.0	13.8	-40%
II	Cachuela Esperanza (990 MW) and El Bala (1680 MW)	22.0	14.4	-35%
III	Cachuela Esperanza (990 MW), El Bala (1680 MW) and Partially Río Grande Hydro Power Complex (550 MW)	24.5	16.0	-35%
IV	Río Grande Hydro Power Complex (2882 MW)	17.4	9.2	-47%

The cross-border trade potential found by OSeMOSYS SAMBA is always smaller as compared to that of OPTGEN, for the same scenarios. This may occur because of the OSeMOSYS SAMBA more detailed description of the generating capacity expansion

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[13] OPTGEN's results do not specify the destination of the electricity exports.

alternatives in all countries that have internal supply options. Scenario III presents the largest trade potential for Bolivia in both models, although at different levels. OSeMOSYS SAMBA estimates 16 TWh of exports by 2025, which is 35% less than the 24.5 TWh obtained by OPTGEN. It is interesting to note that despite the smaller installed capacity of strategic large hydro projects of Scenario III (3.220 MW) as compared to Scenario I (3.872 MW), the former has a higher cross-border trade potential than the latter. The reason is that in Scenario III the average capacity factor of the hydro projects considered is higher (0.44) than in Scenario I (0.32).

The OSeMOSYS SAMBA modelling also shed light on the long-term (2013-2058) cross-border trade potential according to the four electricity surplus scenarios. The results are presented in Figure 7 and Tables 20 to 23. The level of electricity surplus exported by Bolivia varies depending on the particular scenario from 2025 until 2050. This is due to the characteristics of each strategic large hydro complex, mostly related to installed capacity, capacity factors and associated transmission lines to load centres. From 2050 onwards there is a steady increase of electricity exports from Bolivia to Brazil in all scenarios owing to the high demand in Southeast Brazil. Thereafter, surplus production from the strategic large hydro plants reaches its maximum and new hydro capacity need to be built in Bolivia to export more electricity.

Figure 7 - Bolivia annual electricity exports in OSeMOSYS SAMBA

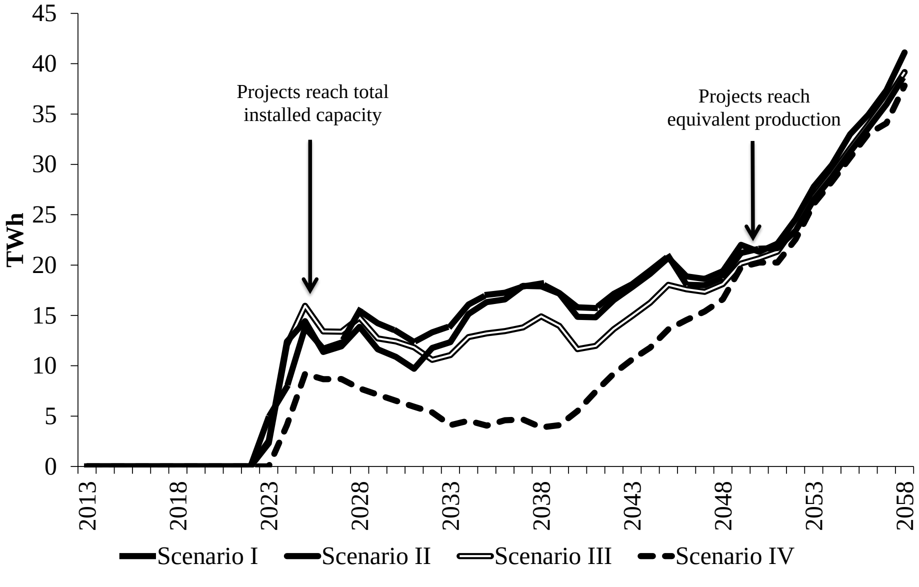

Table 20 - Total Electricity Trade OSeMOSYS SAMBA Scenario I

International Trade (TWh)		Exports										Total Imports	Share
		Argentina	Bolivia	Brazil	Chile	Colombia	Ecuador	Peru	Paraguay	Uruguay	Venezuela		
Imports	**Argentina**	-	-	1	5	-	-	-	196	-	-	202	6%
	Bolivia	-	-	-	-	-	-	-	-	-	-	0	0%
	Brazil	34	658	-	-	-	-	1301	886	6	9	2894	89%
	Chile	5	-	-	-	-	-	-	-	-	-	5	0%
	Colombia	-	-	-	-	-	5	-	-	-	3	8	0%
	Ecuador	-	-	-	-	7	-	3	-	-	-	10	0%
	Peru	-	-	-	-	-	-	-	-	-	-	0	0%
	Paraguay	-	-	-	-	-	-	-	-	-	-	0	0%
	Uruguay	15	-	22	-	-	-	-	-	-	-	37	1%
	Venezuela	-	-	108	-	2	-	-	-	-	-	110	3%
Total Exports		54	658	131	5	9	5	1304	1082	6	12	3266	
Share		2%	20%	4%	0%	0%	0%	40%	33%	0%	0%		

Table 21 - Total Electricity Trade OSeMOSYS SAMBA Scenario II

International Trade (TWh)		Exports										Total Imports	Share
		Argentina	Bolivia	Brazil	Chile	Colombia	Ecuador	Peru	Paraguay	Uruguay	Venezuela		
Imports	**Argentina**	-	-	1	4	-	-	-	196	-	-	201	6%
	Bolivia	-	-	-	-	-	-	-	-	-	-	0	0%
	Brazil	33	679	-	-	-	-	1304	886	6	8	2917	89%
	Chile	5	-	-	-	-	-	-	-	-	-	5	0%
	Colombia	-	-	-	-	-	5	-	-	-	3	9	0%
	Ecuador	-	-	-	-	7	-	4	-	-	-	11	0%
	Peru	-	-	-	-	-	-	-	-	-	-	0	0%
	Paraguay	-	-	-	-	-	-	-	-	-	-	0	0%
	Uruguay	16	-	23	-	-	-	-	-	-	-	38	1%
	Venezuela	-	-	110	-	2	-	-	-	-	-	112	3%
Total Exports		53	679	134	4	9	5	1308	1082	6	12	3293	
Share		2%	21%	4%	0%	0%	0%	40%	33%	0%	0%		

Table 22 - Total Electricity Trade OSeMOSYS SAMBA Scenario III

International Trade (TWh)		Exports										Total Imports	Share
		Argentina	Bolivia	Brazil	Chile	Colombia	Ecuador	Peru	Paraguay	Uruguay	Venezuela		
Imports	**Argentina**	-	-	1	4	-	-	-	197	-	-	202	6%
	Bolivia	-	-	-	-	-	-	-	-	-	-	0	0%
	Brazil	33	635	-	-	-	-	1305	888	6	8	2875	88%
	Chile	5	-	-	-	-	-	-	-	-	-	5	0%
	Colombia	-	-	-	-	-	5	-	-	-	3	9	0%
	Ecuador	-	-	-	-	7	0	4	-	-	0	10	0%
	Peru	-	-	-	-	-	-	-	-	-	-	0	0%
	Paraguay	-	-	-	-	-	-	-	-	-	-	0	0%
	Uruguay	16	-	23	-	-	-	-	-	-	-	38	1%
	Venezuela	-	-	110	-	2	-	-	-	-	-	112	3%
Total Exports		53	635	133	4	9	5	1309	1084	6	12	3251	
Share		2%	20%	4%	0%	0%	0%	40%	33%	0%	0%		

Table 23 - Total Electricity Trade OSeMOSYS SAMBA Scenario IV

International Trade (TWh)		Exports										Total Imports	Share
		Argentina	Bolivia	Brazil	Chile	Colombia	Ecuador	Peru	Paraguay	Uruguay	Venezuela		
Imports	**Argentina**	-	9	-	4	-	-	-	195	-	-	208	7%
	Bolivia	-	-	-	-	-	-	-	-	-	-	0	0%
	Brazil	35	471	-	-	-	-	1322	897	6	9	2739	88%
	Chile	5	-	-	-	-	-	-	-	-	-	5	0%
	Colombia	-	-	-	-	-	5	-	-	-	3	9	0%
	Ecuador	-	-	-	-	7	0	3	-	-	-	10	0%
	Peru	-	-	-	-	-	-	-	-	-	-	0	0%
	Paraguay	-	-	-	-	-	-	-	-	-	-	0	0%
	Uruguay	16	-	22	-	-	-	-	-	-	-	38	1%
	Venezuela	-	-	106	-	2	-	-	-	-	-	108	3%
Total Exports		56	480	129	4	9	5	1325	1092	6	12	3118	
Share		2%	15%	4%	0%	0%	0%	42%	35%	0%	0%		

Scenario II, which considers the construction of the Cachuela Esperanza and El Bala dams (additional installed capacity of 2.670 MW, the smaller in the scenarios modelled), is the one with higher cross-border trade potential for Bolivia, with exports to Brazil up to 679 TWh, which compares with 658 TWh, 635 TWh and 471 TWh in the Scenarios I, III and IV respectively. Scenario IV also shows a potential trade up to 9 TWh from Bolivia to Argentina. Appendix F presents detailed data of the installed capacity expansion in Bolivia as modelled in SAMBA Scenarios.

As results obtained from Scenario II in OSeMOSYS SAMBA are those which present the largest exports potential for Bolivia in the long-run, we develop in the next section the theoretical bargaining power of Bolivia for Scenario II vis-a-vis other countries on the continent, using the Shapley value concept from Cooperative Games.

4.7 Bolivia's Theoretical Bargaining Power in OSeMOSYS SAMBA

Departing from the cross-border electricity trade potential in Scenario II obtained with OSeMOSYS SAMBA and using a cooperative games approach—notably the Shapley value concept—we get the theoretical bargaining power of Bolivia, Brazil and other countries. These highlight the contribution each country brings to the total cross-border trade potential in the continent.

In cooperative games, the Shapley value draws from the idea of a fair distribution of payoffs. It can be obtained by calculating the expected contribution of each player to the total payoff of the grand coalition, which is formed by all players participating in the game. It's important to stress that all coalitions must be equally probable, with players joining in randomly. The calculated value represents a player's bargaining power, and since it represents the player's average contribution to the coalition, it is the fair amount the player should receive from the profit sharing among themselves (Naveiro *et al.*, 2009).

The Shapley value was calculated using the method proposed by Straffin (1993), in which the calculation can be simplified by focusing on an individual player and asking how often and how much he contributes to forming the grand coalition. When player i joins the forming grand coalition, he and the players who have already joined make up a coalition S, of size s, containing i players. The amount of value (v) i contributes is $v(S) - v(S - i)$. Furthermore, this contribution occurs for exactly those orderings in which i is preceded by the $s-1$ other players in S, and followed by the $n-s$ players not in S. The number of orderings in which this happens is $(s-1)!\,(n-s)!$. Hence we get the following expression for the Shapley value of players i:

$$\varphi_i = \frac{1}{n!}\sum_{i\,\in\,S}(s-1)!\,(n-s)!\,[v(S)-v(S-i)] \qquad (s = the\ size\ of\ S)$$

The summation is over all coalitions S which contains i and there are 2^{n-1} such coalitions. In the OSeMOSYS SAMBA scenarios, where 10 countries (players) participate—Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Peru, Paraguay, Uruguay and Venezuela—, to identify the bargaining power of a given country its contribution has to be calculated by the summation over all the 512 (or 2^9) possible coalitions it could join. This calculation was carried out through an algorithm developed in Scilab (2016) and presented in Appendix B.

As shown in Table 24, Bolivia presents a bargaining power equivalent to 10% of the total cross-border electricity trade, in spite of accounting for 21% of the exports (679 TWh) which makes the country the third major exporter. Brazil has the largest bargaining power on the continent (46%) as it is the most important electricity importer (1.525 TWh), notably from Paraguay, Peru and Bolivia. Thus, Paraguay and Peru also have significant bargaining powers, of 20% and 16%, respectively. The Shapley value approach in OSeMOSYS SAMBA was applied to the accumulated potential trade (2013-2058) since the analysis focuses on the long-term electricity trade (imports and exports), though the concept may be applied to identify the bargaining power of the countries in short-term studies.

Table 24 - Theoretical Bargaining Power in Scenario II

Scenario	Countries	Total Potential Trade (TWh)	Exports (TWh)	% of Cross-border Trade Profit	Shapley Value (TWh equivalent)	Theoretical Bargaining Power
Scenario II	Argentina	**3293**	53	2%	127	4%
	Bolivia		**679**	**21%**	**339**	**10%**
	Brazil		**134**	**4%**	**1525**	**46%**
	Chile		4	0%	5	0%
	Colombia		9	0%	9	0%
	Ecuador		5	0%	8	0%
	Paraguay		1308	40%	654	20%
	Peru		1082	33%	541	16%
	Uruguay		6	0%	22	1%
	Venezuela		12	0%	62	2%

The scenario highlights the competition in the long-term among three countries, Paraguay, Peru and Bolivia, to export their electricity surplus to Brazil, the only potential importer. This comprehensive perspective could assist Brazilian and Bolivian policy makers to reach a fair energy trade agreement during the negotiation of the planned strategic hydro projects, by providing a better understanding of the power systems dynamics in the continent. The Shapley value approach applied to long-term power integration planning might therefore stimulate countries to cooperate, which in turn results in higher energy security and better use of energy resources.

4.8 Conclusion and Policy Implications

The Bolivian government plans to become a major electricity exporter in South America. Yet Bolivia is still in the first steps of these plans and will demand more studies to inform on its long-term cross-border trade potential. The scenarios comparison obtained by OPTGEN and OSeMOSYS SAMBA provide a better understanding of how energy models might support policy makers in finding new perspectives of power integration processes, either by including or excluding different assumptions, according to each country's viewpoint.

Despite providing a very good representation of the Bolivian power system, OPTGEN consider very little information about its neighboring countries, thus lacking to take into account their competitive electricity surplus trade potential. On the other hand, OSeMOSYS SAMBA scenarios allow a better representation of the long-term power integration process by incorporating more aggregated data at a national level. Of course, the study described here is an ongoing process and both models could be used in order to find out converging results to support policy makers analyses.

Bolivia has a vast unexploited hydro potential and intends to invest in strategic large hydro complex in the next decades, although its government has limited financial capacity to implement these projects. As Brazilian policy makers face increasing local and international pressure over building more dams in the Amazon forest, the funding of strategic large hydro projects abroad could represent a viable alternative to benefit from a large remaining potential in Brazil's generation mix. Indeed, the Cachuela Esperanza dam was already considered in the Brazilian energy plan for 2014-2023 (EPE, 2014b), although not included in the last two ten-year plans (EPE, 2015a; EPE, 2016). Of course, concerns about environmental impacts and social sustainability of large hydropower plants remain as key issues to be discussed, but they fall beyond the scope of the present paper.

The results from the OSeMOSYS SAMBA scenarios suggests that Bolivia could improve their power infrastructure through trade agreements with Brazil, while increasing its national budget thanks to the electricity trade and reduced fossil fuel spending, which nowadays plays an important role in its natural gas power plants based generating mix.

Moreover, OSeMOSYS SAMBA scenarios indicate that the electricity surplus from strategic large hydro projects in Bolivia might be an interesting supply option especially for Brazil. Therefore, the Bolivian government should focus on bilateral trade agreements with its bigger neighbor in order to become a major electricity exporter in the continent, although additional research is required to assess the cost-competitiveness of Bolivian large hydro projects.

Additionally, as the study’s scope is the electricity system rather than the whole energy sector, further developments on the integrated energy resources planning analysis might provide broader insights. These might include, for example, the need for gas power plants in the Bolivian energy expansion plans to consume surplus non-associated gas in order to give a destination to condensates and natural gas liquids, considering lower imports requirements from Brazil and Argentina.

The Shapley value approach for cooperative games applied to the OSeMOSYS SAMBA scenarios clarifies the amount of electricity trade each country brings to the integration process, thus acting as a decision support tool for helping policy makers to reach more suitable trade agreements in a bilateral relationship. The theoretical bargaining power of Bolivia in the long-run cross-border electricity trade potential is equivalent to 10% (or 339 TWh), rivalling the country to Peru and Paraguay—who are potential major exports as well—to supply Brazilian electricity demand.

Finally, it is important to underline that the theoretical bargaining powers identified in this study are subject to many other aspects—especially political ones—and therefore cannot be qualified as definitive, but rather as part of an ongoing process.

5 Terceiro ensaio: Large-Scale Renewable Power Potential in South America and Nationally Determined Contributions: An OSeMOSYS SAMBA Scenario Modelling[14]

5.1 Abstract

The penetration of renewable energy in the power sector is a key strategy to foster the transition towards a less fossil fuel dependent society. This study presents a methodology to identify non-hydro large-scale renewable electricity potential in South America aiming at the establishment of a sustainable low-carbon power system. It focuses on generation opportunities from wind, solar, biomass and geothermal sources. OSeMOSYS, a cost-optimization tool for long-term energy planning, is used to develop least cost supply system configurations for the South America Model Base – SAMBA. The scenario considered was built upon the Nationally Determined Contributions (NDC), as detailed by the twenty-first session of the Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC). For a 2050 horizon, the results envisioned through the projection of power systems show that large hydropower will still play an important role in the continent by 2050, but other renewables, like wind farms, geothermal, concentrated solar and biomass power plants together, may reach 28% of total electricity generation.

5.2 Highlights

We model the long-term dynamics of power systems in South America.

The large-scale renewable electricity potential investments are discussed.

Brazil, Chile and Argentina have the largest potential for renewable investments.

The approach might support policy makers to build strategies for energy security and mitigation measures.

5.3 Keywords

Long-term Power Systems Modelling; Renewable Power Penetration; OSeMOSYS SAMBA; Large-scale Renewable Electricity Potential;

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5.4 Introduction

The structure of the South American power matrix defines the continent as a leader in the use of renewable sources for electricity generation from. In 2013, the share of renewable sources in electricity production reached 65%, mainly due to the large continental hydro potential (CIER, 2014). Despite its vast renewable energy sources other than hydropower — such as wind, solar, geothermal and biomass — the current power mix of South America is not diversified, as shown in Table 25. Therefore, the continent could take advantage of its privileged position to enhance the participation of different renewable resources and consequentely reach an even more sustainable energy supply.

Table 25 - South America's power supply in 2013
Source: Based on (CIER, 2014)

Source	Electricity Production (TWh)	Share (%)
Hydro	674.2	60.3%
Non-renewable (Oil, Natural Gas, Coal, Nuclear)	387.8	34.7%
Other renewables (Wind, Solar, Biomass)	56.2	5.0%
Total	1118.2	

This paper studies the possibility of achieving a more sustainable power mix in South America by identifying the potential use of non-hydro large-scale renewable sources in the expansion of the continent's power sector, through 2050. Three technology groups were considered in the generation expansion planning: Hydro (hydropower, including large and small plants); Non-renewable (power plants fuelled by oil derivatives, natural gas, coal, nuclear and other non-renewables sources); and Renewable (Concentrated Solar Power and Photovoltaics, biomass incineration, second generation biogas, as well as on-shore and off-shore wind farms and geothermal plants). The latter group is the focus of this study.

Several barriers hinder the fast adoption of large-scale renewable technologies in the power sector, especially in the supply side: high costs, slow returns and access to capital for large-scale investment; competitive disadvantages; limited development leaps; and reliability. In addition, the adoption of low-carbon technologies is influenced — either positively or negatively — by the following factors: governmental policy; regulatory uncertainty; markets; local communities and social pressure; attitudes and social values; technological opportunities; know-how and organizational capabilities (Narayanamurti *et al.*, 2011; Montalvo, 2008; Oliveira *et al.*, 2016).

The Nationally Determined Contributions (NDC) Scenario for the generation expansion planning considered here takes into account current trends of the South American power matrix as well as the NDC as detailed by the twenty-first session of the Conference of the Parties (COP21) of the U.N. Framework Convention on Climate Change (UNFCCC), held in Paris in December 2015 (PBL, 2016). The intention here is not to evaluate South America's strategic and competitive industrial advantages, but rather to analyze political strategies and policy instruments to foster renewable generation, so as to meet explicit needs of final electricity demand and concurrently promoting a sustainable future.

This paper is organized in four sections, besides this introduction. Section 4.5 presents the methodological approach used together with the tools to implement it, while section 4.6 presents the basic assumptions considered in the analysis. The 4.7 section discusses the results obtained and the section 4.8 draws some conclusions.

5.5 Structure of OSeMOSYS SAMBA

OSeMOSYS is an open source, dynamic, bottom-up, multi-year and multi-regional energy system modelling framework that employs linear optimization techniques to determine the minimum cost long-term investment strategy and energy technology mix required to satisfy an exogenously defined energy demand. The framework assumes price-inelastic demand, perfect competition and perfect foresight. Although simplifying some of the dynamics underlying energy systems, the linear structure allows OSeMOSYS to analyze ample time and space domains with limited computational efforts, thus providing some policy indications (Howells *et al.*, 2011; OSeMOSYS, 2015).

OSeMOSYS is a full-fledged systems optimization model for long-run energy planning written in the open source programming language GNU Mathprog. Unlike other energy systems models (such as MARKAL/TIMES, MESSAGE, PRIMES, EFOM and POLES), OSeMOSYS is not a "closed package", featuring a flexibility in design which enables its application to different systems and requires a less significant learning curve and time commitment to build and operate. Besides, no upfront financial investment is necessary since it does not use proprietary software or commercial programming languages and solvers. Therefore, communities of students, business analysts, government specialists and developing country energy researchers are able to contribute to a pool of shared knowledge about energy modelling (Howells *et al.*, 2011; OSeMOSYS, 2015).

All models in OSeMOSYS are based on the concept of Reference Energy System (RES), a schematic and intuitive representation of the energy conversion and supply chain from the extraction of the primary fuels to the final consumption. The transferred commodities, or energy vectors (e.g. primary fuels, processed fuels, electricity at transmission level, electricity at distribution level, final commodity at consumers), are called ‘fuels’, while the processes using or producing them are called ‘technologies’. The RES shows the types of technologies that are available to each country as well as the final demands that they participate in serving. Each country is equipped with national options for fossil fuel extraction as well as relevant import options. The different countries are represented by parallel and separate sets of energy chains leading to the respective country level demands (Howells *et al.*, 2011; OSeMOSYS, 2015).

The OSeMOSYS South America Model Base (SAMBA) was developed in 2015 by the authors in order to develop long-term power sector expansion scenarios for South America. An extensive bibliographical search was carried out to identify power sector features of ten countries: Argentina (MPF, 2013; CNEA, 2015a; CNEA, 2015b; CAMMESA, 2015a; CAMMESA, 2015b), Bolivia (AE, 2012a; AE, 2012b; AE, 2013; MHE, 2014a; MHE, 2014b), Brazil (EPE, 2012; EPE, 2013; EPE, 2014a; EPE, 2014b; EPE, 2014c; EPE, 2015a; EPE, 2015b; ONS, 2014; ONS, 2015a; ONS, 2015b; MME, 2006; MME, 2014), Chile (CDEC SING, 2012; CDEC SIC, 2013; MEN, 2014; MEN, 2015); Colombia (MME, 2011; UPME, 2013; SIEL, 2015); Ecuador (MEER, 2012; CONELEC, 2013; ARCONEL, 2014a; ARCONEL, 2014b); Paraguay (ANDE, 2015; VMME, 2014; VMME, 2015); Peru (MEM, 2014a; MEM, 2014b; COES SINAC, 2013; COES SINAC, 2015); Uruguay (DNE, 2005; DNE, 2013; ADME, 2015a; ADME, 2015b) and Venezuela (CNG, 2008; MPPEE, 2013a; MPPEE, 2013b; MPPEE, 2014; CORPOELEC, 2015).

International organization reports also provided important data: World Energy Outlook (WEO) 2014 (IEA WEO, 2014), Energy Technologies Perspectives (ETP) (IEA ETP, 2012; IEA ETP, 2014; IEA ETP, 2015), and ETSAP Technology Brief (IEA ETSAP, 2010a; IEA ETSAP, 2010b; IEA ETSAP, 2010c; IEA ETSAP, 2010d; IEA

ETSAP, 2010e; IEA ETSAP, 2010f; IEA ETSAP, 2013a; IEA ETSAP, 2013b; IEA ETSAP, 2014). OSeMOSYS SAMBA main features are presented in table 26.

Table 26 - OSeMOSYS SAMBA model main characteristics
Source: Based on (Howells *et al.*, 2011; OSeMOSYS, 2015; AE, 2012a; EPE, 2014b; UPME, 2013; MEER, 2012; MEM, 2014b; MPPEE, 2013; IEA, 2012; IEA WEO 2014)

	OSeMOSYS SAMBA
Methodology	Linear programming
Sectoral scope	Integrated model that partially represents the entire energy system
Technology changes	Exogenous learning curves based on IEA ETP reports
Storages	Equivalent hydro reservoirs for Brazil and Venezuela
Time resolution	12 months; 4 intra-day periods
Time horizon	2013-2050; Yearly steps
User-constraint /policy options	Available, depends on scenario definition
Geographical coverage	13 individual country-level system models (4 subsystems in Brazil)
Computational efficiency	Medium running time - 180 minutes
Power system operation	Energy balance only, based on intra-day energy production profiles
Reserve margin	15%; Only dispachable technologies are able to meet the reserve margin
Accounting	Real discount rate applied is 8%; Monetary unit is 2013 US$
Times zones	1st: Argentina, Brazil (Southeast, Northeast and South regions) and Uruguay; 2nd: Bolivia, Brazil (North), Chile, Paraguay and Venezuela; 3rd: Colombia, Ecuador and Peru.

Each country within SAMBA has one global electricity exogenous demand that represents national consumption and includes all consumption sectors. The electricity demand growth rates are based on ten-year historical data (2004-2013), national plans projections and consider two groups of countries: Argentina, Brazil (South and Southeast subsystems), Chile, Uruguay and Venezuela, with higher per capita electricity consumption (more than 2.000 kWh per year) and Bolivia, Brazil (North and Northeast), Colombia, Ecuador, Paraguay and Peru, with lower per capita electricity consumption (less than 2.000 kWh per year). As Table 27 shows, the former group presents lower growth rates than the latter, since the consumption is expected to increase more in countries where the consumption per capita is lower.

Fifteen electricity production technologies were considered: large and small (< 30 MW) hydroelectric plants; bagasse thermal power plants (incineration and biogas from bagasse); geothermal power plants; wind farms (on-shore and off-shore); large solar plants (photovoltaic and Concentrated Solar Power); coal plants (pulverized and Clean Coal with Carbon Capture and Storage), fuel oil thermal plants; natural gas (open cycle and combined cycle); and nuclear power plants.

Table 27 - Electricity Demand Growth Rates by 2050
Source: Own elaboration based on AE, 2012a; EPE, 2014b; UPME, 2013; MEER, 2012; MEM, 2014b; MPPEE, 2013; IEA, 2012; IEA WEO 2014)

Country	2013-2025	2026-2030	2031-2040	2041-2045	2046-2050
Argentina	2.5%	3.0%	4.0%	3.5%	3.0%
Bolivia	3.0%	3.5%	4.5%	4.0%	3.5%
Brazil North	3.0%	3.5%	4.5%	4.0%	3.5%
Brazil Northeast	3.0%	3.5%	4.5%	4.0%	3.5%
Brazil South	2.5%	3.0%	4.0%	3.5%	3.0%
Brazil Southeast	2.5%	3.0%	4.0%	3.5%	3.0%
Chile	2.5%	3.0%	4.0%	3.5%	3.0%
Colombia	3.0%	3.5%	4.5%	4.0%	3.5%
Ecuador	3.0%	3.5%	4.5%	4.0%	3.5%
Paraguay	3.0%	3.5%	4.5%	4.0%	3.5%
Peru	3.0%	3.5%	4.5%	4.0%	3.5%
Uruguay	2.5%	3.0%	4.0%	3.5%	3.0%
Venezuela	2.5%	3.0%	4.0%	3.5%	3.0%

Decentralized generation was not taken into account and features related to investment costs, fixed costs, variable costs, inflexibility, capacity factors, efficiency expected lifetime and construction time for each of the generating technologies are presented in the Appendix D. Concerning the fuel availability for generating electricity, domestic prices were used when available in national reports, otherwise international prices were employed. Further, it is assumed that government subsidies affect long-term energy prices causing them to converge, by 2050, towards international prices.

The amount of energy resources available for generating electricity were identified either for non-renewable (oil, natural gas, coal and uranium) and renewable (biomass, wind, solar, geothermal and hydro) sources. As this study focuses on (non-hydro) large-scale renewable potential, a brief description of the availability of the latter is presented as follows:

Geothermal - An important unexploited potential is located mainly in Andean countries, such as Bolivia, Colombia and Ecuador, who foresee the use of geothermal power plants in their medium-term expansion plans (AE, 2012a; UPME, 2013; MEER, 2012). The main potentials are in Peru (3 GW), Argentina, Bolivia, Ecuador, Colombia, Chile (2 GW each country) and Venezuela (1 GW) (OLADE, 2013).

Wind - The on-shore wind potential of the continent has been estimated by several studies through distinct methodologies (MEM, 2014a; Camargo Schubert *et al.*, 2011; Dicco, 2012; Ferreno, 2013; Santana *et al.*, 2014; Longatt *et al.*, 2014; Mattar *et al.*, 2014). As for the off-shore, wind potential of the continent data availability is more precarious. Because of that, instead of a maximum value for the exploitation of wind potential, constraints on the maximum annual investment in wind generation capacity, along the lines defined in (Lu *et al.*, 2009), for both on-shore and off-shore wind generation were considered. Therefore, countries with annual potentials of more than 500 TWh (on-shore) and 30 TWh (off-shore) had a 1GW/year capacity addition limit, while countries with smaller annual potentials had a limit of 100 MW/year. In the case of Argentina, because of its impressive (although unofficial) potentials — which reach 42.000 TWh (on-shore) and 5.000 TWh (off-shore) — the maximum annual investment was set to 2 GW.

Solar - Some studies estimate the solar potential in Chile (Santana *et al.*, 2014) and Brazil (Pereira *et al.*, 2006), and field reports have assessed the environmental and economic feasibility of large centralized solar generation (EPE, 2012). A Geographic Information System (GIS) was used in (Trieb *et al.*, 2009) to assess the feasibility of solar power plants combining solar resource data with data for land use, topography, hydrology, geomorphology, infrastructure, and protected areas, to exclude those sites that are technically unfit for the building of solar plants. Argentina, Bolivia, Brazil, Chile and Peru exhibit important areas for large-scale electricity production using Concentrated Solar Power (CSP) plants, with an average annual irradiation higher than 2.000 kWh per square meter. For these countries, a maximum installed capacity investment per year of up to 1 GW for CSP was assumed, while Colombia and Venezuela who have areas with lesser average annual irradiation (between 1.500 kWh and 2.000 kWh per square meter), the maximum capacity investment per year was limited to 100 MW. The same assumptions were applied to investments in large-scale solar photovoltaic plants.

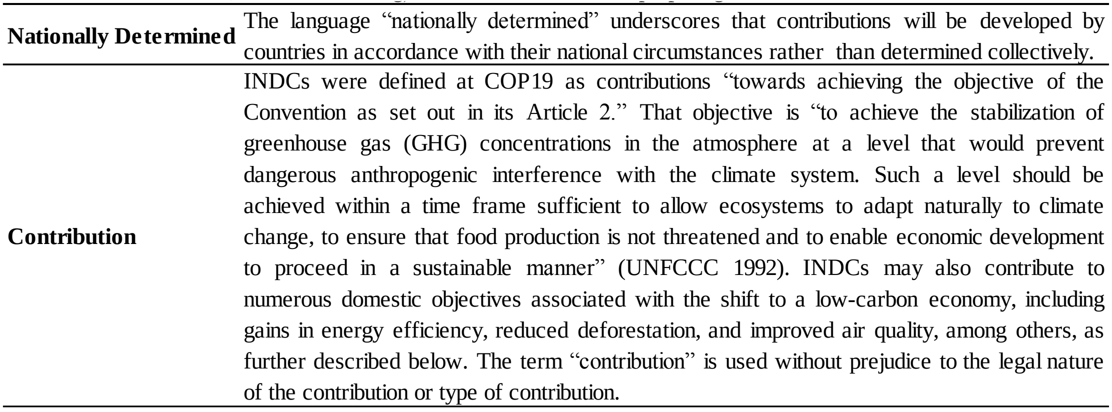
Biomass - To avoid discussions related the competition for land and water between food and biofuels, it was assumed that only sugarcane was used for electricity generation. Indeed, bioelectricity in the continent is mostly produced from the incineration of sugarcane bagasse (first generation biofuel) (EPE, 2014b). The historical production of bagasse in each country was identified (UN, 2015) and projected throughout the study horizon at an annual increase rate of 2%. The amount of sugarcane destined to electricity generation was assumed to be up to 25% of the total annual production, and a further 25% could be used to produce lignocellulosic biogas (second generation) for fuel thermal plants, after 2020.

Finally, the expansion of installed biomass generation capacity in the medium term (2013-2018) corresponds exactly to the new power plants projects scheduled in government plans of the following countries: Bolivia (AE, 2012a), Brazil (EPE, 2014b), Colombia (UPME, 2013), Ecuador (MEER, 2012), Peru (MEM, 2014b) and Venezuela (MPPEE, 2013). For Argentina, Chile, Paraguay and Uruguay the expansion is based on (PLATTS, 2015). Results for system expansion from 2019 onwards are less constrained and relate directly to the OSeMOSYS SAMBA optimization process.

5.6 OSeMOSYS SAMBA NDC Scenario

By 15 December 2015, 188 countries (97% of global greenhouse gas emissions in 2012) had submitted their Nationally Determined Contributions (NDC) in the Paris Agreement (PBL, 2016). As Table 28 shows, in their individual NDCs countries should outline their post-2020 climate actions to communicate internationally how they would cut emissions, adjusting their contributions along national priorities, capabilities, and responsibilities. These individual measures — if ambitious enough — can be the basis for collective action and set a path towards a low-carbon and climate-resilient future of the planet (UNDP, 2015).

Table 28 - Nationally Determined Contributions
Source: Based on (UNDP, 2015)



Nationally Determined	The language “nationally determined” underscores that contributions will be developed by countries in accordance with their national circumstances rather than determined collectively.
Contribution	INDCs were defined at COP19 as contributions “towards achieving the objective of the Convention as set out in its Article 2.” That objective is “to achieve the stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner” (UNFCCC 1992). INDCs may also contribute to numerous domestic objectives associated with the shift to a low-carbon economy, including gains in energy efficiency, reduced deforestation, and improved air quality, among others, as further described below. The term “contribution” is used without prejudice to the legal nature of the contribution or type of contribution.

The OSeMOSYS SAMBA NDC Scenario looks at the implications of ensuring that each country in South America honors their detailed emission commitments, in order to secure determined climate change mitigation goals. Types of mitigation commitments and pledges observed in the past have been quite diverse, ranging from economy-wide emission limitation or reduction targets, to policies, projects and energy actions. However, with the NDC detailed information for Argentina, Brazil, Chile, Colombia, Peru, as well as a baseline emissions assumption for the other South American countries, the constraints included in OSeMOSYS SAMBA NDC Scenario for the total carbon emission from the national power sectors were set as follows (PBL, 2016):

- Argentina - Reduce greenhouse gas emissions by 15%, compared to baseline emission projections, by 2030;
- Brazil - Reduce greenhouse gas emissions by 43%, below 2005 levels, by 2030;
- Chile - Reduction in CO_2 emissions intensity (emissions per unit of GDP) by 30% by 2030, compared to 2007 levels;
- Colombia - Reduce greenhouse gas emissions by 20%, as compared to baseline emission projections, by 2030;
- Peru - Reduce greenhouse gas emissions by 20%, as compared to baseline emission projections, by 2030;
- Other countries in South America - Keep greenhouse gas emissions according to baseline emission projections by 2030;
- From 2030 onwards, the maximum annual emission limits for the national power sectors in all countries were kept constant.

According to (PBL, 2016), NDCs are *"insufficient to put the world directly on a pathway to secure a likely chance to stay below 2°C."* Actually, if all measures outlined by the counties in their NDCs were implemented, there would still be an emissions gap of 14 Gt CO_2 equivalent, in terms of the global emissions level needed to maintain a temperature increase below 2°C.

5.7 Scenario Results

Results obtained for the OSeMOSYS SAMBA NDC scenario are presented for the years 2013, 2030 and 2050. The initial years (2013-2018) were modelled according to short-term national plans by setting special generating capacity constraints on the optimization process. This approach poses limitations to the features which characterize bottom-up energy models, since competition between various technologies, cost and performance should not be fixed (Block, 2007), as they are in the OSeMOSYS SAMBA NDC scenario. Thus, for the medium term (by 2030), we may only say that results suggest a “Probable Potential” since by that time the effects of the mentioned imposed constraints become less effective. For the longer term (2031-2050), the techno-economic analysis has limited use as the range of possible technologies becomes less visible, thus suggesting only a “Possible Potential”.

By 2030, the installed capacity from renewable plants (non-hydro) reaches 55 GW, accounting for 16% of the total generation capacity in South America. The correspondent electricity generation is 175 TWh or 11% of the total production in 2030. Considering a possible potential by 2050, the renewable generation could reach 37% of the total installed capacity or 28% of the electricity production in the continent. Hydro will remain the main electricity source in South America, but non-renewable power plants would still expand both capacity and production, although their shares drop, as Table 29 shows.

Table 29 - OSeMOSYS SAMBA NDC Power Production and Installed Capacity

Technology group	**Installed Capacity**			**Electricity Production**		
	2013	**2030**	**2050**	**2013**	**2030**	**2050**
	GW			TWh		
Renewables	12.2	55.0	230.9	54.0	175.8	702.0
Hydro	143.5	210.5	275.3	687.2	950.3	1249.7
Non-renewables	78.3	86.1	120.7	273.8	402.6	515.3
Total	234.0	351.7	626.8	1015.0	1528.6	2467.1
	Share			Share		
Renewables	5%	16%	37%	5%	11%	28%
Hydro	61%	60%	44%	68%	62%	51%
Non-renewables	33%	24%	19%	27%	26%	21%

The investment costs obtained from the OSeMOSYS SAMBA NDC scenario, total and by country, are shown in Tables 30 and 31, respectively. In the medium term, the new renewable power plants in the continent would require a US$ 77.4 billion investment to expand the generating capacity up to 46.6 GW. This investment goes mostly to on-shore wind (36.4 GW), biomass incineration (8.3 GW) and geothermal (1.9 GW) expansion. In country wise terms, Brazil (US$ 29 billion), Chile (US$ 25 billion) and Argentina (US$ 17 billion) have the largest renewable generating capacity investment potentials by 2030, basically associated to the exploitation of on-shore wind resources. The long term indicates US$ 363.1 billion in possible investments by 2050, notably from on-shore wind, CSP and biomass incineration.

Table 30 - OSeMOSYS SAMBA NDC Large Scale Renewable Generation Potential

Technology	Investment Cost (USD Billion)		Installed Capacity (GW)	
	2013-2030	2031-2050	2013-2030	2031-2050
Biogas	0.0	10.8	0.0	4.4
Biomass Incineration	15.9	61.9	8.3	32.5
CSP	0.0	91.8	0.0	36.6
Geothermal	6.6	26.8	1.9	9.4
PV	0.2	5.2	0.1	5.1
Wind Off-shore	0.0	13.8	0.0	5.2
Wind On-shore	54.8	152.8	36.4	110.8
Total	77.4	363.1	46.6	204.0

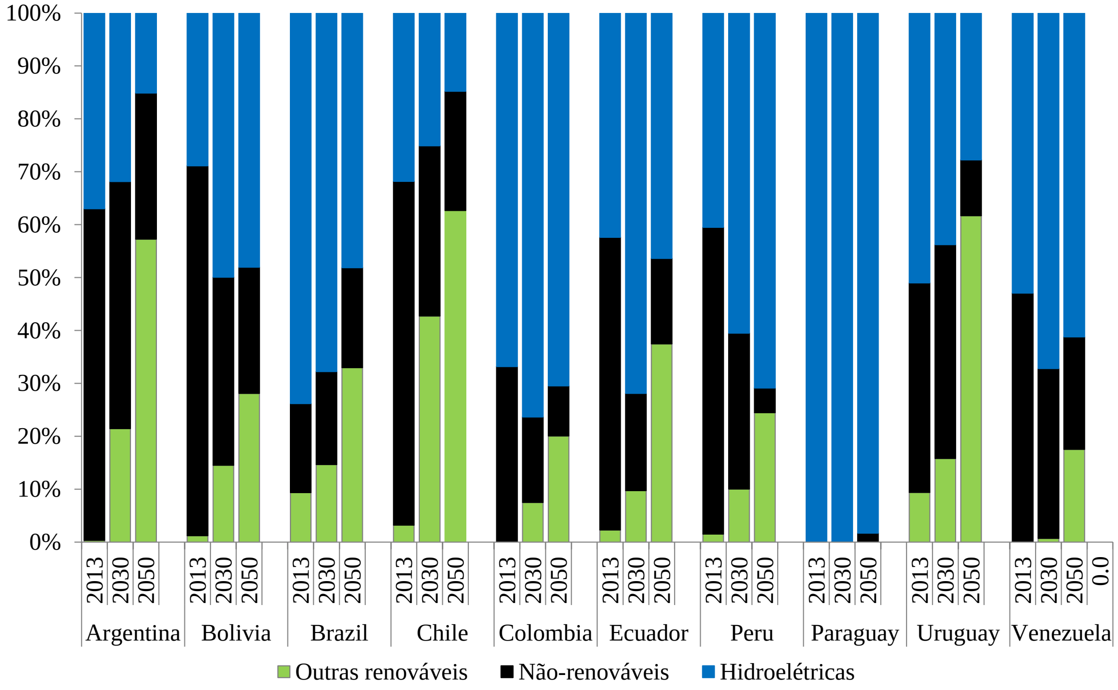
Table 31 - OSeMOSYS SAMBA NDC Medium term renewable plants investment costs by country

Cumulative Investment Costs 2013-2030 (USD Billion)	Argentina	Bolivia	Brazil	Chile	Colombia	Ecuador	Paraguay	Peru	Uruguay	Venezuela	South America
Biogas	-	-	-	-	-	-	-	-	-	-	-
Biomass Incineration	2.49	0.51	4.66	2.08	2.43	0.85	-	1.78	0.73	0.33	15.86
CSP	-	-	-	-	-	-	-	-	-	-	-
Geothermal	-	0.39	-	5.93	-	0.30	-	-	-	-	6.62
PV	0.01	-	-	0.15	-	-	-	-	-	-	0.15
Wind Off-shore	-	-	-	-	-	-	-	-	-	-	-
Wind On-shore	11.87	-	24.41	17.04	0.59	0.34	-	0.15	0.24	0.12	54.77
Total	14.38	0.89	29.07	25.20	3.02	1.49	-	1.93	0.97	0.45	77.40

It is worth to highlight that second generation biogas fueled power plants, large CSP and off-shore wind farms are not cost-competitive throughout the medium term (up to 2030) in the OSeMOSYS SAMBA NDC scenario, although they exhibit investment potentials in the long term, as pointed out in Table 30.

Figure 8 depicts the shares of renewable, non-renewable and hydro plants in national installed capacity, from a country perspective. By 2030, the renewable power plants in Chile, Argentina and Uruguay would represent approximately 20% of the total capacity, reaching the critical level of 60% by 2050. Nevertheless, some studies indicate that the technically maximum acceptable share of renewables in instantaneous generation is limited to 70% (De Jongue *et al.*, 2011; Pina *et al.*, 2013). Paraguay, a major hydroelectricity exporter in the continent, does not show any new renewable plant potential investment, as the increase of Paraguayan electricity demand is met by a decrease in the amount of electricity exported.

Figure 8 - OSeMOSYS SAMBA NDC Generating Capacity Shares



5.8 Conclusion and Policy Implications

The OSeMOSYS SAMBA NDC Scenario had the objective to provide some insights on how the South American countries may contribute to the global reduction of carbon emissions by increasing their share of renewable sources, especially large scale. Considering that each country faces unique circumstances — such as different emissions profiles and emissions reduction opportunities, as well as different resource needs and different risks from a changing climate — the results obtained may help in defining policy goals and strategies to foster its renewable generating capacity potential in the medium and long term.

South American power sector is highly dependent on hydro generation and will remain so by 2050, although other renewable generation should become more important, by supplying 11% and 28% of the total electricity on the continent by 2030 and 2050, respectively. The share of renewable generating capacity is expected to increase in all countries but Paraguay, due to the country's large hydroelectricity availability. In the medium term, Argentina, Brazil and Chile exhibit the largest renewable potentials, mostly from on-shore wind farms, biomass (bagasse) incineration and geothermal plants. In the OSeMOSYS SAMBA NDC scenario, second generation biogas fueled power plants, large concentrated solar plants and off-shore wind farms will be cost-competitive only in the long term (by 2050).

As a final word, despite the limitations akin to large scale models, the OSeMOSYS SAMBA NDC scenario may provide important information for policy makers, especially those related to an accurate representation of renewable energy technologies, whose participation is ever increasing. Long-term energy planning is uncertain and the decision to invest in renewable generation should take into account the stage of technological and knowledge development in different countries. Of course, the study described here is an ongoing process, as different assumptions could be either added or withdrawn, as a function of the focus intended and data availability.

6. Conclusões e considerações finais

A extensa revisão bibliográfica realizada para identificar as características dos setores elétricos dos onze países modelados nos cenários construídos no SAMBA permitiu ampliar a compreensão do processo de integração elétrica no continente e sua dinâmica no longo-prazo. A abordagem apresentada no OSeMOSYS SAMBA baseia-se fundamentalmente em uma integração produtiva no longo-prazo, em vez de uma integração comercial de curto-prazo, ou seja, para além da simples comercialização de sobras de energia elétrica. Os resultados apresentados neste trabalho refletem impactos de políticas energéticas, considerando perspectivas de integração e de limites das emissões em cada país.

Atualmente há elevada dependência da geração hidroelétrica pelos países do continente, fato que deverá permanecer além de 2050, apesar de a geração por outras fontes renováveis se tornar importante no longo-prazo, correspondendo a 11% da produção elétrica total em 2030 e 28% do total em 2050. Os cenários SAMBA indicam que a participação da capacidade de geração renovável aumentará em todos os países, exceto no Paraguai devido à grande disponibilidade de energia hidroelétrica[15].

O Brasil, por sua posição destacada no continente e conhecimento na operação do SIN, será agente fundamental para consolidação de um sistema elétrico internacional. A integração dos sistemas elétricos a partir da perspectiva brasileira, a qual considera o financiamento de grandes projetos hidroelétricos no exterior, resulta para o País a manutenção de uma matriz elétrica com baixos custos operacionais e baixa dependência externa.

Países com grandes potenciais hidroelétricos inexplorados e com limitada capacidade financeira como a Bolívia e a Guiana, poderiam desenvolver suas infraestruturas elétricas através de acordos internacionais de venda de excedentes de eletricidade no longo-prazo ao Brasil, com impactos positivos nos orçamentos nacionais, até mesmo pela redução de gastos com combustíveis fósseis para a produção de eletricidade.

---

[15] A referência à “geração renovável” está relacionada aqui às novas tecnologias de geração renováveis, tais como eólica, solar, geotérmica, biogás, uma vez que a geração hidroelétrica pode ser considerada como uma “geração renovável madura”.

Além disso, os cenários SAMBA indicam que o Peru se tornaria o maior exportador de eletricidade para o Brasil, uma vez que avança na exploração de seu potencial hidroelétrico localizado na Amazônia. Entretanto, a sustentabilidade socioambiental de tais projetos é questionável, pois provavelmente provocarão alterações irreversíveis em ecossistemas muito sensíveis e na qualidade de vida das populações atingidas.

As mudanças nos setores elétricos da América do Sul apresentadas nos cenários SAMBA têm impactos consideráveis nos poderes de barganhas teóricos de cada país, com destaque para o aumento da influência do Brasil que ultrapassa o Paraguai como país mais influente no comércio internacional de eletricidade do continente, sobretudo por se constituir em maior importador.

Bolívia, Peru e Paraguai, os maiores potenciais exportadores ao Brasil, apresentariam poderes de barganha semelhantes e se rivalizariam para atender ao suprimento de parte da demanda elétrica brasileira. A Bolívia, assim como o Peru, possui grandes potenciais hidroelétricos inexplorados e pretende viabilizar complexos estratégicos de usinas hidroelétricas nas próximas décadas, apesar da reduzida capacidade financeira nacional para implementar tais projetos.

A abordagem do Valor de Shapley para jogos cooperativos aplicada aos cenários SAMBA destaca o poder de barganha que cada país possui, ou melhor, a contribuição de cada um para o processo de integração elétrica, uma informação sensível para a formulação de acordos internacionais de comércio que seriam os mais recomendados e adequados para os projetos de integração considerados.

É importante destacar que os poderes de barganha teóricos identificados neste trabalho estão sujeitos à influência de outras variáveis, especialmente políticas e, portanto, não devem ser qualificados como definitivos, mas, sim, como parte de um processo mais amplo de um sistema de apoio à tomada de decisão de investimentos.

Em suma, a integração elétrica exige que se proceda com cautela. Apesar de possivelmente ser viável nas esferas técnica e econômica, no campo político o cenário é muito nebuloso. O processo de integração fará sentido apenas com a consolidação de governos democráticos que proporcionem estabilidade institucional e respeitem os contratos no âmbito do direito internacional. As mudanças nos cenários macroeconômicos e políticos dos países sul-americanos, com destaque para as crises no

Brasil e, principalmente, na Venezuela, com forte recessão econômica e perturbação da ordem democrática desde 2015, impactam negativamente o processo de integração regional, e consequentemente os projetos de integração elétrica.

Apesar das limitações inerentes aos modelos energéticos de longo-prazo, o OSeMOSYS SAMBA é uma ferramenta útil e transparente para auxiliar no processo de decisão de investimentos, pois permite a análise de impactos de políticas energéticas tais como aquelas relacionadas à integração elétrica e de fontes renováveis, cuja participação apresenta crescimento constante e sólido. O planejamento energético de longo-prazo está sujeito a inúmeras incertezas, sobretudo políticas. Além disso, o processo de tomada de decisão em projetos de geração renovável deve considerar o estágio de desenvolvimento tecnológico e a capacidade financeira de diferentes países.

Como consideração final, é fundamental destacar que há muitas dificuldades relacionadas à precificação *ex ante* e *ex post* da eletricidade comercializada em interconexões internacionais, uma vez que cada país possui o seu próprio operador nacional e regulamentação setorial característica. Essa situação constitui barreiras enormes ao processo de integração, como destacado por Hira e Amaya (2003). Consequentemente, apesar do grande potencial de comércio internacional de eletricidade, notadamente de fontes de geração renováveis, o avanço da coordenação dos sistemas elétricos na América do Sul permanece ainda uma intenção.

Para contribuir na superação dessa barreira, futuras pesquisas derivadas deste trabalho deverão ter como objeto de estudo aspectos regulatórios. As legislações ambientais dos países devem ser comparadas, uma vez que o nível de regulamentação relacionada às medidas de mitigação dos impactos de grandes usinas hidroelétricas pode alterar significativamente a viabilidade técnica e econômica dos projetos de integração. As legislações dos setores elétricos também precisam ser comparadas, uma vez que os desenhos dos mercados elétricos são bastante distintos, com a presença de empresas privadas e estatais em diferentes níveis em cada país. Propostas para a harmonização das regulamentações ambiental e setorial poderão viabilizar novos projetos de integração elétrica e poderão proporcionar maior coordenação produtiva no longo-prazo.

Apêndice (Appendix) A – OSeMOSYS Code

```
# Open Source energy Modelling SYStem
# ==============================================================================
#    Copyright [2010-2013] [OSeMOSYS Forum steering committee see: www.osemosys.org]
#   Licensed under the Apache License, Version 2.0 (the "License");
#   you may not use this file except in compliance with the License.
#   You may obtain a copy of the License at http://www.apache.org/licenses/LICENSE-2.0
#   Unless required by applicable law or agreed to in writing, software distributed under the License is distributed on an "AS IS"
#   BASIS, WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
#   See the License for the specific language governing permissions and limitations under the License.
# ==============================================================================
#                              Model Definition
###############
#    Sets     #
###############
#
set YEAR;
set TECHNOLOGY;
set TIMESLICE;
set FUEL;
set EMISSION;
set MODE_OF_OPERATION;
set REGION;
set SEASON;
set DAYTYPE;
set DAILYTIMEBRACKET;
set FLEXIBLEDEMANDTYPE;
set STORAGE;
#
#####################
#    Parameters     #
#####################
#
param SalvageFactor{r in REGION, t in TECHNOLOGY, y in YEAR};
#  Global
param YearSplit{l in TIMESLICE, y in YEAR};
param DiscountRate{r in REGION, t in TECHNOLOGY};
param DaySplit{lh in DAILYTIMEBRACKET, y in YEAR};
param Conversionls{l in TIMESLICE, ls in SEASON};
param Conversionld{l in TIMESLICE, ld in DAYTYPE};
param Conversionlh{l in TIMESLICE, lh in DAILYTIMEBRACKET};
param DaysInDayType{ls in SEASON, ld in DAYTYPE, y in YEAR};
param TradeRoute{r in REGION, rr in REGION, f in FUEL, y in YEAR};
param DepreciationMethod{r in REGION};

########                              Demands                              ########
param SpecifiedAnnualDemand{r in REGION, f in FUEL, y in YEAR};
param SpecifiedDemandProfile{r in REGION, f in FUEL, l in TIMESLICE, y in YEAR};
param AccumulatedAnnualDemand{r in REGION, f in FUEL, y in YEAR};
```

```
#########                    Performance                ########
param CapacityToActivityUnit{r in REGION, t in TECHNOLOGY};
param TechWithCapacityNeededToMeetPeakTS{r in REGION, t in TECHNOLOGY};
param CapacityFactor{r in REGION, t in TECHNOLOGY, l in TIMESLICE, y in YEAR};
param AvailabilityFactor{r in REGION, t in TECHNOLOGY, y in YEAR};
param OperationalLife{r in REGION, t in TECHNOLOGY};
param ResidualCapacity{r in REGION, t in TECHNOLOGY, y in YEAR};
param InputActivityRatio{r in REGION, t in TECHNOLOGY, f in FUEL, m in MODE_OF_OPERATION, y in YEAR};
param OutputActivityRatio{r in REGION, t in TECHNOLOGY, f in FUEL, m in MODE_OF_OPERATION, y in YEAR};

#########                    Technology Costs                #############
param CapitalCost{r in REGION, t in TECHNOLOGY, y in YEAR};
param VariableCost{r in REGION, t in TECHNOLOGY, m in MODE_OF_OPERATION, y in YEAR};
param FixedCost{r in REGION, t in TECHNOLOGY, y in YEAR};

#########              Storage                #############
param TechnologyToStorage{r in REGION, t in TECHNOLOGY, s in STORAGE, m in MODE_OF_OPERATION};
param TechnologyFromStorage{r in REGION, t in TECHNOLOGY, s in STORAGE, m in MODE_OF_OPERATION};
param StorageLevelStart{r in REGION, s in STORAGE};
param StorageMaxChargeRate{r in REGION, s in STORAGE};
param StorageMaxDischargeRate{r in REGION, s in STORAGE};
param MinStorageCharge{r in REGION, s in STORAGE, y in YEAR};
param OperationalLifeStorage{r in REGION, s in STORAGE};
param CapitalCostStorage{r in REGION, s in STORAGE, y in YEAR};
param DiscountRateStorage{r in REGION, s in STORAGE};
param ResidualStorageCapacity{r in REGION, s in STORAGE, y in YEAR};

#########                    Capacity Constraints         #############
param CapacityOfOneTechnologyUnit{r in REGION, t in TECHNOLOGY, y in YEAR};
param TotalAnnualMaxCapacity{r in REGION, t in TECHNOLOGY, y in YEAR};
param TotalAnnualMinCapacity{r in REGION, t in TECHNOLOGY, y in YEAR};

#########                    Investment Constraints          #############
param TotalAnnualMaxCapacityInvestment{r in REGION, t in TECHNOLOGY, y in YEAR};
param TotalAnnualMinCapacityInvestment{r in REGION, t in TECHNOLOGY, y in YEAR};

#########                    Activity Constraints         #############
param TotalTechnologyAnnualActivityUpperLimit{r in REGION, t in TECHNOLOGY, y in YEAR};
param TotalTechnologyAnnualActivityLowerLimit{r in REGION, t in TECHNOLOGY, y in YEAR};
param TotalTechnologyModelPeriodActivityUpperLimit{r in REGION, t in TECHNOLOGY};
param TotalTechnologyModelPeriodActivityLowerLimit{r in REGION, t in TECHNOLOGY};
param MinElecGeneration{r in REGION, t in TECHNOLOGY, l in TIMESLICE, y in YEAR};
param MinElecGeneration{r in REGION, t in TECHNOLOGY, y in YEAR};
param MinGenerationTagTechonology{r in REGION, t in TECHNOLOGY};

#########                    Reserve Margin                        #############
param ReserveMarginTagTechnology{r in REGION, t in TECHNOLOGY, y in YEAR};
param ReserveMarginTagFuel{r in REGION, f in FUEL, y in YEAR};
param ReserveMargin{r in REGION, f in FUEL, y in YEAR};
```

```
#########                                   RE Generation Target              #############
param RETagTechnology{r in REGION, t in TECHNOLOGY, y in YEAR};
param RETagFuel{r in REGION, f in FUEL, y in YEAR};
param REMinProductionTarget{r in REGION, y in YEAR};

#########                                   Emissions & Penalties                         #############
param EmissionActivityRatio{r in REGION, t in TECHNOLOGY, e in EMISSION, m in MODE_OF_OPERATION, y in YEAR};
param EmissionsPenalty{r in REGION, e in EMISSION, y in YEAR};
param AnnualExogenousEmission{r in REGION, e in EMISSION, y in YEAR};
param AnnualEmissionLimit{r in REGION, e in EMISSION, y in YEAR};
param ModelPeriodExogenousEmission{r in REGION, e in EMISSION};
param ModelPeriodEmissionLimit{r in REGION, e in EMISSION};

######################
#   Model Variables  #
######################

var DemandByTimeSlice{r in REGION, f in FUEL, l in TIMESLICE, y in YEAR};
var FuelProductionByTimeSlice{r in REGION, f in FUEL, l in TIMESLICE, y in YEAR};
var TotalAnnualCapacity{r in REGION, t in TECHNOLOGY, y in YEAR};
var AnnualProductionByTechnology{r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR};
var AnnualUseByTechnology{r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR};
var ProductionByTechnologyByTimeSlice{r in REGION, t in TECHNOLOGY, f in FUEL, l in TIMESLICE, y in YEAR};
#var UseByTechnologyByTimeSlice{r in REGION, t in TECHNOLOGY, f in FUEL, l in TIMESLICE, y in YEAR};
var AnnualEmissions{r in REGION, e in EMISSION, y in YEAR};
var AnnualEmissionsByTechnology{r in REGION, t in TECHNOLOGY, e in EMISSION, y in YEAR};

########                          Demands                          ########
#var RateOfDemand{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}>= 0;
#var Demand{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}>= 0;

########                          Storage                          #############
var NewStorageCapacity{r in REGION, s in STORAGE, y in YEAR} >=0;
var SalvageValueStorage{r in REGION, s in STORAGE, y in YEAR} >=0;
var StorageLevelYearStart{r in REGION, s in STORAGE, y in YEAR} >=0;
var StorageLevelYearFinish{r in REGION, s in STORAGE, y in YEAR} >=0;
var StorageLevelSeasonStart{r in REGION, s in STORAGE, ls in SEASON, y in YEAR} >=0;
var StorageLevelDayTypeStart{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, y in YEAR} >=0;
var StorageLevelDayTypeFinish{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, y in YEAR} >=0;
#var RateOfStorageCharge{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in
YEAR};
#var RateOfStorageDischarge{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in
YEAR};
#var NetChargeWithinYear{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in
YEAR};
#var NetChargeWithinDay{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in
YEAR};
#var StorageLowerLimit{r in REGION, s in STORAGE, y in YEAR}>=0;
#var StorageUpperLimit{r in REGION, s in STORAGE, y in YEAR} >=0;
#var AccumulatedNewStorageCapacity{r in REGION, s in STORAGE, y in YEAR} >=0;
#var CapitalInvestmentStorage{r in REGION, s in STORAGE, y in YEAR} >=0;
```

```
#var DiscountedCapitalInvestmentStorage{r in REGION, s in STORAGE, y in YEAR} >=0;
#var DiscountedSalvageValueStorage{r in REGION, s in STORAGE, y in YEAR} >=0;
#var TotalDiscountedStorageCost{r in REGION, s in STORAGE, y in YEAR} >=0;

#########                    Capacity Variables                    #############
var WBResidualCapacity{r in REGION, t in TECHNOLOGY, y in YEAR};
var NumberOfNewTechnologyUnits{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0,integer;
var NewCapacity{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0;
var AccumulatedNewCapacity{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0;
var TotalCapacityAnnual{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0;

#########                    Activity Variables              #############
var RateOfActivity{r in REGION, l in TIMESLICE, t in TECHNOLOGY, m in MODE_OF_OPERATION, y in YEAR} >= 0;
var UseByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR}>= 0;
var Trade{r in REGION, rr in REGION, l in TIMESLICE, f in FUEL, y in YEAR};
var UseAnnual{r in REGION, f in FUEL, y in YEAR}>= 0;
#var RateOfTotalActivity{r in REGION, t in TECHNOLOGY, l in TIMESLICE, y in YEAR} >= 0;
var TotalTechnologyAnnualActivity{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0;
#var TotalAnnualTechnologyActivityByMode{r in REGION, t in TECHNOLOGY, m in MODE_OF_OPERATION, y in
YEAR}>=0;
#var RateOfProductionByTechnologyByMode{r in REGION, l in TIMESLICE, t in TECHNOLOGY, m in
MODE_OF_OPERATION, f in FUEL, y in YEAR}>= 0;
#var RateOfProductionByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR}>= 0;
#var ProductionByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR}>= 0;
#var ProductionByTechnologyAnnual{r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR}>= 0;
#var RateOfProduction{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR} >= 0;
#var Production{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR} >= 0;
#var RateOfUseByTechnologyByMode{r in REGION, l in TIMESLICE, t in TECHNOLOGY, m in MODE_OF_OPERATION, f
in FUEL, y in YEAR}>= 0;
#var RateOfUseByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR} >= 0;
#var UseByTechnologyAnnual{r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR}>= 0;
#var RateOfUse{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}>= 0;
#var Use{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}>= 0;
#var TradeAnnual{r in REGION, rr in REGION, f in FUEL, y in YEAR};
#var ProductionAnnual{r in REGION, f in FUEL, y in YEAR}>= 0;

#########                    Costing Variables               #############
var CapitalInvestment{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0;
var DiscountedCapitalInvestment{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0;
var VariableOperatingCost{r in REGION, t in TECHNOLOGY, l in TIMESLICE, y in YEAR}>= 0;
var SalvageValue{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0;
var DiscountedSalvageValue{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0;
var OperatingCost{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0;
#var DiscountedOperatingCost{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0;
var AnnualVariableOperatingCost{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0;
var AnnualFixedOperatingCost{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0;
var TotalDiscountedCostByTechnology{r in REGION, t in TECHNOLOGY, y in YEAR}>= 0;
var TotalDiscountedCost{r in REGION, y in YEAR}>= 0;
var ModelPeriodCostByRegion{r in REGION} >= 0;

#########                         Reserve Margin                         #############
```

```
#var TotalCapacityInReserveMargin{r in REGION, y in YEAR}>= 0;
#var DemandNeedingReserveMargin{r in REGION,l in TIMESLICE, y in YEAR}>= 0;

#########			RE Gen Target			#############
#var TotalREProductionAnnual{r in REGION, y in YEAR};
#var RETotalDemandOfTargetFuelAnnual{r in REGION, y in YEAR};
#var TotalTechnologyModelPeriodActivity{r in REGION, t in TECHNOLOGY};

#########			Emissions		#########
#var DiscountedTechnologyEmissionsPenalty{r in REGION, t in TECHNOLOGY, y in YEAR};
#var ModelPeriodEmissions{r in REGION, e in EMISSION}>= 0;
#var AnnualTechnologyEmissionByMode{r in REGION, t in TECHNOLOGY, e in EMISSION, m in MODE_OF_OPERATION, y in YEAR};
#var AnnualTechnologyEmission{r in REGION, t in TECHNOLOGY, e in EMISSION, y in YEAR};
#var AnnualTechnologyEmissionPenaltyByEmission{r in REGION, t in TECHNOLOGY, e in EMISSION, y in YEAR};
var AnnualTechnologyEmissionsPenalty{r in REGION, t in TECHNOLOGY, y in YEAR};
#var AnnualEmissions{r in REGION, e in EMISSION, y in YEAR}>= 0;
#	table data IN "CSV" "data.csv": s <- [FROM,TO], d~DISTANCE, c~COST;
#	table capacity IN "CSV" "SpecifiedAnnualDemand.csv": [YEAR, FUEL, REGION], SpecifiedAnnualDemand~ColumnNameInCSVSheet;

######################
# Objective Function #
######################

minimize cost: sum{r in REGION, t in TECHNOLOGY, y in YEAR} (((((sum{yy in YEAR: y-yy < OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y])*FixedCost[r,t,y] + sum{m in MODE_OF_OPERATION, l in TIMESLICE} RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*VariableCost[r,t,m,y])/((1+DiscountRate[r,t])^(y-min{yy in YEAR} min(yy)+0.5))+CapitalCost[r,t,y] * NewCapacity[r,t,y]/((1+DiscountRate[r,t])^(y-min{yy in YEAR} min(yy)))-DiscountedSalvageValue[r,t,y]) + sum{s in STORAGE} (CapitalCostStorage[r,s,y] * NewStorageCapacity[r,s,y]/((1+DiscountRateStorage[r,s])^(y-min{yy in YEAR} min(yy)))-CapitalCostStorage[r,s,y] * NewStorageCapacity[r,s,y]/((1+DiscountRateStorage[r,s])^(y-min{yy in YEAR} min(yy)))));

#####################
# Constraints	#
#####################

#s.t. EQ_SpecifiedDemand{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}: SpecifiedAnnualDemand[r,f,y]*SpecifiedDemandProfile[r,f,l,y] / YearSplit[l,y]=RateOfDemand[r,l,f,y];

#########		Capacity Adequacy A		#############
s.t. CAa1_TotalNewCapacity{r in REGION, t in TECHNOLOGY, y in YEAR}:AccumulatedNewCapacity[r,t,y] = sum{yy in YEAR: y-yy < OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy];

s.t. CAa2_TotalAnnualCapacity{r in REGION, t in TECHNOLOGY, y in YEAR}: ((sum{yy in YEAR: y-yy < OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y]) = TotalCapacityAnnual[r,t,y];

#s.t. CAa3_TotalActivityOfEachTechnology{r in REGION, t in TECHNOLOGY, l in TIMESLICE, y in YEAR}: sum{m in MODE_OF_OPERATION} RateOfActivity[r,l,t,m,y] = RateOfTotalActivity[r,t,l,y];
```

```
s.t. CAa4_Constraint_Capacity{r in REGION, l in TIMESLICE, t in TECHNOLOGY, y in YEAR}: sum{m in
MODE_OF_OPERATION} RateOfActivity[r,l,t,m,y] <= ((sum{yy in YEAR: y-yy < OperationalLife[r,t] && y-yy>=0}
NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y])*CapacityFactor[r,t,l,y]*CapacityToActivityUnit[r,t];

s.t. CAa5_TotalNewCapacity{r in REGION, t in TECHNOLOGY, y in YEAR: CapacityOfOneTechnologyUnit[r,t,y]<>0}:
CapacityOfOneTechnologyUnit[r,t,y]*NumberOfNewTechnologyUnits[r,t,y] = NewCapacity[r,t,y];
# Note that the PlannedMaintenance equation below ensures that all other technologies have a capacity great enough to at least meet
the annual average.

#########            Capacity Adequacy B                   #############
s.t. CAb1_PlannedMaintenance{r in REGION, t in TECHNOLOGY, y in YEAR}: sum{l in TIMESLICE} sum{m in
MODE_OF_OPERATION} RateOfActivity[r,l,t,m,y]*YearSplit[l,y] <= sum{l in TIMESLICE} (((sum{yy in YEAR: y-yy <
OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y])*CapacityFactor[r,t,l,y]*YearSplit[l,y])*
AvailabilityFactor[r,t,y]*CapacityToActivityUnit[r,t];

#########                 Energy Balance A                 #############
#s.t. EBa1_RateOfFuelProduction1{r in REGION, l in TIMESLICE, f in FUEL, t in TECHNOLOGY, m in
MODE_OF_OPERATION, y in YEAR: OutputActivityRatio[r,t,f,m,y] <>0}:
RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y]  = RateOfProductionByTechnologyByMode[r,l,t,m,f,y];

#s.t. EBa2_RateOfFuelProduction2{r in REGION, l in TIMESLICE, f in FUEL, t in TECHNOLOGY, y in YEAR}: sum{m in
MODE_OF_OPERATION: OutputActivityRatio[r,t,f,m,y] <>0} RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y] =
RateOfProductionByTechnology[r,l,t,f,y] ;

#s.t. EBa3_RateOfFuelProduction3{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}: sum{m in
MODE_OF_OPERATION, t in TECHNOLOGY: OutputActivityRatio[r,t,f,m,y] <>0}
RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y]  =  RateOfProduction[r,l,f,y];

#s.t. EBa4_RateOfFuelUse1{r in REGION, l in TIMESLICE, f in FUEL, t in TECHNOLOGY, m in MODE_OF_OPERATION, y
in YEAR: InputActivityRatio[r,t,f,m,y]<>0}: RateOfActivity[r,l,t,m,y]*InputActivityRatio[r,t,f,m,y]  =
RateOfUseByTechnologyByMode[r,l,t,m,f,y];

#s.t. EBa5_RateOfFuelUse2{r in REGION, l in TIMESLICE, f in FUEL, t in TECHNOLOGY, y in YEAR}: sum{m in
MODE_OF_OPERATION: InputActivityRatio[r,t,f,m,y]<>0} RateOfActivity[r,l,t,m,y]*InputActivityRatio[r,t,f,m,y] =
RateOfUseByTechnology[r,l,t,f,y];

#s.t. EBa6_RateOfFuelUse3{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}: sum{m in MODE_OF_OPERATION, t in
TECHNOLOGY: InputActivityRatio[r,t,f,m,y]<>0} RateOfActivity[r,l,t,m,y]*InputActivityRatio[r,t,f,m,y]  = RateOfUse[r,l,f,y];
#s.t. EBa7_EnergyBalanceEachTS1{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}: sum{m in
MODE_OF_OPERATION, t in TECHNOLOGY: OutputActivityRatio[r,t,f,m,y] <>0}
RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y]*YearSplit[l,y] = Production[r,l,f,y];

#s.t. EBa8_EnergyBalanceEachTS2{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}: sum{m in
MODE_OF_OPERATION, t in TECHNOLOGY: InputActivityRatio[r,t,f,m,y]<>0}
RateOfActivity[r,l,t,m,y]*InputActivityRatio[r,t,f,m,y]*YearSplit[l,y] = Use[r,l,f,y];

#s.t. EBa9_EnergyBalanceEachTS3{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}:
SpecifiedAnnualDemand[r,f,y]*SpecifiedDemandProfile[r,f,l,y] = Demand[r,l,f,y];

s.t. EBa10_EnergyBalanceEachTS4{r in REGION, rr in REGION, l in TIMESLICE, f in FUEL, y in YEAR}: Trade[r,rr,l,f,y] = -
Trade[rr,r,l,f,y];
```

```
s.t. EBa11_EnergyBalanceEachTS5{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}: sum{m in
MODE_OF_OPERATION, t in TECHNOLOGY: OutputActivityRatio[r,t,f,m,y] <>0}
RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y]*YearSplit[l,y] >=
SpecifiedAnnualDemand[r,f,y]*SpecifiedDemandProfile[r,f,l,y] + sum{m in MODE_OF_OPERATION, t in TECHNOLOGY:
InputActivityRatio[r,t,f,m,y]<>0} RateOfActivity[r,l,t,m,y]*InputActivityRatio[r,t,f,m,y]*YearSplit[l,y] + sum{rr in REGION}
Trade[r,rr,l,f,y]*TradeRoute[r,rr,f,y];

#########		Energy Balance B			#############
#s.t. EBb1_EnergyBalanceEachYear1{r in REGION, f in FUEL, y in YEAR}: sum{m in MODE_OF_OPERATION, t in
TECHNOLOGY, l in TIMESLICE: OutputActivityRatio[r,t,f,m,y] <>0}
RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y]*YearSplit[l,y] = ProductionAnnual[r,f,y];

#s.t. EBb2_EnergyBalanceEachYear2{r in REGION, f in FUEL, y in YEAR}: sum{m in MODE_OF_OPERATION, t in
TECHNOLOGY, l in TIMESLICE: InputActivityRatio[r,t,f,m,y]<>0}
RateOfActivity[r,l,t,m,y]*InputActivityRatio[r,t,f,m,y]*YearSplit[l,y] = UseAnnual[r,f,y];

#s.t. EBb3_EnergyBalanceEachYear3{r in REGION, rr in REGION, f in FUEL, y in YEAR}: sum{l in TIMESLICE}
Trade[r,rr,l,f,y] = TradeAnnual[r,rr,f,y];

#s.t. EBb4_EnergyBalanceEachYear4{r in REGION, f in FUEL, y in YEAR}: sum{m in MODE_OF_OPERATION, t in
TECHNOLOGY, l in TIMESLICE: OutputActivityRatio[r,t,f,m,y] <>0}
RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y]*YearSplit[l,y] >= sum{m in MODE_OF_OPERATION, t in
TECHNOLOGY, l in TIMESLICE: InputActivityRatio[r,t,f,m,y]<>0}
RateOfActivity[r,l,t,m,y]*InputActivityRatio[r,t,f,m,y]*YearSplit[l,y] + sum{l in TIMESLICE, rr in REGION}
Trade[r,rr,l,f,y]*TradeRoute[r,rr,f,y] + AccumulatedAnnualDemand[r,f,y];

#########		Accounting Technology Production/Use	#############
#s.t. Acc1_FuelProductionByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR}: sum{m
in MODE_OF_OPERATION: OutputActivityRatio[r,t,f,m,y] <>0} RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y] *
YearSplit[l,y] = ProductionByTechnology[r,l,t,f,y];

#s.t. Acc2_FuelUseByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR}: sum{m in
MODE_OF_OPERATION: InputActivityRatio[r,t,f,m,y]<>0} RateOfActivity[r,l,t,m,y]*InputActivityRatio[r,t,f,m,y] *
YearSplit[l,y] = UseByTechnology[r,l,t,f,y];

#s.t. Acc3_AverageAnnualRateOfActivity{r in REGION, t in TECHNOLOGY, m in MODE_OF_OPERATION, y in YEAR}:
sum{l in TIMESLICE} RateOfActivity[r,l,t,m,y]*YearSplit[l,y] = TotalAnnualTechnologyActivityByMode[r,t,m,y];
####s.t. Acc4_ModelPeriodCostByRegion{r in REGION}:sum{t in TECHNOLOGY, y in YEAR}(((((sum{yy in YEAR: y-yy <
OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y])*FixedCost[r,t,y] + sum{m in
MODE_OF_OPERATION, l in TIMESLICE}
RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*VariableCost[r,t,m,y])/((1+DiscountRate[r,t])^(y-min{yy in YEAR}
min(yy)+0.5))+CapitalCost[r,t,y] * NewCapacity[r,t,y]/((1+DiscountRate[r,t])^(y-min{yy in YEAR}
min(yy)))+DiscountedTechnologyEmissionsPenalty[r,t,y]-DiscountedSalvageValue[r,t,y]) + sum{s in STORAGE}
(CapitalCostStorage[r,s,y] * NewStorageCapacity[r,s,y]/((1+DiscountRateStorage[r,s])^(y-min{yy in YEAR} min(yy)))-
CapitalCostStorage[r,s,y] * NewStorageCapacity[r,s,y]/((1+DiscountRateStorage[r,s])^(y-min{yy in YEAR} min(yy))))) =
ModelPeriodCostByRegion[r];

#########		Storage Equations			#############
#s.t. S1_RateOfStorageCharge{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y
in YEAR}: sum{t in TECHNOLOGY, m in MODE_OF_OPERATION, l in TIMESLICE:TechnologyToStorage[r,t,s,m]>0}
```

```
RateOfActivity[r,l,t,m,y] * TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh] =
RateOfStorageCharge[r,s,ls,ld,lh,y];

#s.t. S2_RateOfStorageDischarge{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET,
y in YEAR}: sum{t in TECHNOLOGY, m in MODE_OF_OPERATION, l in TIMESLICE:TechnologyFromStorage[r,t,s,m]>0}
RateOfActivity[r,l,t,m,y] * TechnologyFromStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh] =
RateOfStorageDischarge[r,s,ls,ld,lh,y];

#s.t. S3_NetChargeWithinYear{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y
in YEAR}: sum{l in TIMESLICE:Conversionls[l,ls]>0&&Conversionld[l,ld]>0&&Conversionlh[l,lh]>0}  (sum{t in
TECHNOLOGY, m in MODE_OF_OPERATION:TechnologyToStorage[r,t,s,m]>0} (RateOfActivity[r,l,t,m,y] *
TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] * TechnologyFromStorage[r,t,s,m] *
Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh])) * YearSplit[l,y] * Conversionls[l,ls] * Conversionld[l,ld] *
Conversionlh[l,lh] = NetChargeWithinYear[r,s,ls,ld,lh,y];

#s.t. S4_NetChargeWithinDay{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y
in YEAR}: ((sum{t in TECHNOLOGY, m in MODE_OF_OPERATION, l in TIMESLICE:TechnologyToStorage[r,t,s,m]>0}
RateOfActivity[r,l,t,m,y] * TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in
TECHNOLOGY, m in MODE_OF_OPERATION, l in TIMESLICE:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y]
* TechnologyFromStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh])) * DaySplit[lh,y] =
NetChargeWithinDay[r,s,ls,ld,lh,y];
s.t. S5_and_S6_StorageLevelYearStart{r in REGION, s in STORAGE, y in YEAR}: if y = min{yy in YEAR} min(yy) then
StorageLevelStart[r,s]

                                                        else StorageLevelYearStart[r,s,y-1] + sum{ls in SEASON, ld in DAYTYPE,
lh in DAILYTIMEBRACKET} sum{l in TIMESLICE:Conversionls[l,ls]>0&&Conversionld[l,ld]>0&&Conversionlh[l,lh]>0}
(sum{t in TECHNOLOGY, m in MODE_OF_OPERATION:TechnologyToStorage[r,t,s,m]>0} (RateOfActivity[r,l,t,m,y] *
TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] * TechnologyFromStorage[r,t,s,m] *
Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh])) * YearSplit[l,y] * Conversionls[l,ls] * Conversionld[l,ld] *
Conversionlh[l,lh]

                                                        = StorageLevelYearStart[r,s,y];
s.t. S7_and_S8_StorageLevelYearFinish{r in REGION, s in STORAGE, y in YEAR}: if y < max{yy in YEAR} max(yy) then
StorageLevelYearStart[r,s,y+1]

                                                        else StorageLevelYearStart[r,s,y] + sum{ls in SEASON, ld in DAYTYPE, lh
in DAILYTIMEBRACKET} sum{l in TIMESLICE:Conversionls[l,ls]>0&&Conversionld[l,ld]>0&&Conversionlh[l,lh]>0}  (sum{t
in TECHNOLOGY, m in MODE_OF_OPERATION:TechnologyToStorage[r,t,s,m]>0} (RateOfActivity[r,l,t,m,y] *
TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] * TechnologyFromStorage[r,t,s,m] *
Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh])) * YearSplit[l,y] * Conversionls[l,ls] * Conversionld[l,ld] *
Conversionlh[l,lh]

                                                        = StorageLevelYearFinish[r,s,y];
s.t. S9_and_S10_StorageLevelSeasonStart{r in REGION, s in STORAGE, ls in SEASON, y in YEAR}: if ls = min{lsls in
SEASON} min(lsls) then StorageLevelYearStart[r,s,y]

                                                        else StorageLevelSeasonStart[r,s,ls-1,y] + sum{ld in DAYTYPE, lh in
DAILYTIMEBRACKET} sum{l in TIMESLICE:Conversionls[l,ls]>0&&Conversionld[l,ld]>0&&Conversionlh[l,lh]>0}  (sum{t in
```

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TECHNOLOGY, m in MODE_OF_OPERATION:TechnologyToStorage[r,t,s,m]>0} (RateOfActivity[r,l,t,m,y] *
TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] * TechnologyFromStorage[r,t,s,m] *
Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh])) * YearSplit[l,y] * Conversionls[l,ls] * Conversionld[l,ld] *
Conversionlh[l,lh]

                                                    = StorageLevelSeasonStart[r,s,ls,y];
s.t. S11_and_S12_StorageLevelDayTypeStart{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, y in YEAR}: if ld =
min{ldld in DAYTYPE} min(ldld) then StorageLevelSeasonStart[r,s,ls,y]

                                                    else StorageLevelDayTypeStart[r,s,ls,ld-1,y] + sum{lh in
DAILYTIMEBRACKET} (((sum{t in TECHNOLOGY, m in MODE_OF_OPERATION, l in
TIMESLICE:TechnologyToStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] * TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] *
Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in TECHNOLOGY, m in MODE_OF_OPERATION, l in
TIMESLICE:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] * TechnologyFromStorage[r,t,s,m] * Conversionls[l,ls]
* Conversionld[l,ld] * Conversionlh[l,lh])) * DaySplit[lh,y]) * DaysInDayType[ls,ld-1,y]

                                                    = StorageLevelDayTypeStart[r,s,ls,ld,y];
s.t. S13_and_S14_and_S15_StorageLevelDayTypeFinish{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, y in
YEAR}:    if ls = max{lsls in SEASON} max(lsls) && ld = max{ldld in DAYTYPE} max(ldld) then StorageLevelYearFinish[r,s,y]

                                                    else if ld = max{ldld in DAYTYPE} max(ldld) then
StorageLevelSeasonStart[r,s,ls+1,y]

                                                    else StorageLevelDayTypeFinish[r,s,ls,ld+1,y] - sum{lh in
DAILYTIMEBRACKET} (((sum{t in TECHNOLOGY, m in MODE_OF_OPERATION, l in
TIMESLICE:TechnologyToStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] * TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] *
Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in TECHNOLOGY, m in MODE_OF_OPERATION, l in
TIMESLICE:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] * TechnologyFromStorage[r,t,s,m] * Conversionls[l,ls]
* Conversionld[l,ld] * Conversionlh[l,lh])) * DaySplit[lh,y]) * DaysInDayType[ls,ld+1,y]

                                                    = StorageLevelDayTypeFinish[r,s,ls,ld,y];

##########                    Storage Constraints                         #############

s.t. SC1_LowerLimit_BeginningOfDailyTimeBracketOfFirstInstanceOfDayTypeInFirstWeekConstraint{r in REGION, s in
STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in YEAR}: 0 <=
(StorageLevelDayTypeStart[r,s,ls,ld,y]+sum{lhlh in DAILYTIMEBRACKET:lh-lhlh>0} (((sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION, l in TIMESLICE:TechnologyToStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] *
TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION, l in TIMESLICE:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] *
TechnologyFromStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh])) * DaySplit[lh,y]))-
MinStorageCharge[r,s,y]*(sum{yy in YEAR: y-yy < OperationalLifeStorage[r,s] && y-yy>=0}
NewStorageCapacity[r,s,yy]+ResidualStorageCapacity[r,s,y]);

s.t. SC1_UpperLimit_BeginningOfDailyTimeBracketOfFirstInstanceOfDayTypeInFirstWeekConstraint{r in REGION, s in
STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in YEAR}:
(StorageLevelDayTypeStart[r,s,ls,ld,y]+sum{lhlh in DAILYTIMEBRACKET:lh-lhlh>0} (((sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION, l in TIMESLICE:TechnologyToStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] *
TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION, l in TIMESLICE:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] *
```

```
TechnologyFromStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh])) * DaySplit[lh,y]))-(sum{yy in
YEAR: y-yy < OperationalLifeStorage[r,s] && y-yy>=0} NewStorageCapacity[r,s,yy]+ResidualStorageCapacity[r,s,y]) <= 0;
```

```
s.t. SC2_LowerLimit_EndOfDailyTimeBracketOfLastInstanceOfDayTypeInFirstWeekConstraint{r in REGION, s in STORAGE, ls
in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in YEAR}: 0 <= if ld > min{ldld in DAYTYPE} min(ldld) then
(StorageLevelDayTypeStart[r,s,ls,ld,y]-sum{lhlh in DAILYTIMEBRACKET:lh-lhlh<0} (((sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION, l in TIMESLICE:TechnologyToStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] *
TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION, l in TIMESLICE:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] *
TechnologyFromStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh])) * DaySplit[lh,y]))-
MinStorageCharge[r,s,y]*(sum{yy in YEAR: y-yy < OperationalLifeStorage[r,s] && y-yy>=0}
NewStorageCapacity[r,s,yy]+ResidualStorageCapacity[r,s,y]);
```

```
s.t. SC2_UpperLimit_EndOfDailyTimeBracketOfLastInstanceOfDayTypeInFirstWeekConstraint{r in REGION, s in STORAGE, ls
in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in YEAR}: if ld > min{ldld in DAYTYPE} min(ldld) then
(StorageLevelDayTypeStart[r,s,ls,ld+1,y]-sum{lhlh in DAILYTIMEBRACKET:lh-lhlh<0} (((sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION, l in TIMESLICE:TechnologyToStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] *
TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION, l in TIMESLICE:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] *
TechnologyFromStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh])) * DaySplit[lh,y]))-(sum{yy in
YEAR: y-yy < OperationalLifeStorage[r,s] && y-yy>=0} NewStorageCapacity[r,s,yy]+ResidualStorageCapacity[r,s,y]) <= 0;
```

```
s.t. SC3_LowerLimit_EndOfDailyTimeBracketOfLastInstanceOfDayTypeInLastWeekConstraint{r in REGION, s in STORAGE, ls
in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in YEAR}:  0 <= (StorageLevelDayTypeFinish[r,s,ls,ld,y] -
sum{lhlh in DAILYTIMEBRACKET:lh-lhlh<0} (((sum{t in TECHNOLOGY, m in MODE_OF_OPERATION, l in
TIMESLICE:TechnologyToStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] * TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] *
Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in TECHNOLOGY, m in MODE_OF_OPERATION, l in
TIMESLICE:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] * TechnologyFromStorage[r,t,s,m] * Conversionls[l,ls]
* Conversionld[l,ld] * Conversionlh[l,lh])) * DaySplit[lh,y]))-MinStorageCharge[r,s,y]*(sum{yy in YEAR: y-yy <
OperationalLifeStorage[r,s] && y-yy>=0} NewStorageCapacity[r,s,yy]+ResidualStorageCapacity[r,s,y]);
```

```
s.t. SC3_UpperLimit_EndOfDailyTimeBracketOfLastInstanceOfDayTypeInLastWeekConstraint{r in REGION, s in STORAGE, ls
in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in YEAR}:  (StorageLevelDayTypeFinish[r,s,ls,ld,y] - sum{lhlh in
DAILYTIMEBRACKET:lh-lhlh<0} (((sum{t in TECHNOLOGY, m in MODE_OF_OPERATION, l in
TIMESLICE:TechnologyToStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] * TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] *
Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in TECHNOLOGY, m in MODE_OF_OPERATION, l in
TIMESLICE:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] * TechnologyFromStorage[r,t,s,m] * Conversionls[l,ls]
* Conversionld[l,ld] * Conversionlh[l,lh])) * DaySplit[lh,y]))-(sum{yy in YEAR: y-yy < OperationalLifeStorage[r,s] && y-yy>=0}
NewStorageCapacity[r,s,yy]+ResidualStorageCapacity[r,s,y]) <= 0;
```

```
s.t. SC4_LowerLimit_BeginningOfDailyTimeBracketOfFirstInstanceOfDayTypeInLastWeekConstraint{r in REGION, s in
STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in YEAR}:            0 <= if ld > min{ldld in
DAYTYPE} min(ldld) then (StorageLevelDayTypeFinish[r,s,ls,ld-1,y]+sum{lhlh in DAILYTIMEBRACKET:lh-lhlh>0} (((sum{t
in TECHNOLOGY, m in MODE_OF_OPERATION, l in TIMESLICE:TechnologyToStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y]
* TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION, l in TIMESLICE:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] *
TechnologyFromStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh])) * DaySplit[lh,y]))-
MinStorageCharge[r,s,y]*(sum{yy in YEAR: y-yy < OperationalLifeStorage[r,s] && y-yy>=0}
NewStorageCapacity[r,s,yy]+ResidualStorageCapacity[r,s,y]);
```

```
s.t. SC4_UpperLimit_BeginningOfDailyTimeBracketOfFirstInstanceOfDayTypeInLastWeekConstraint{r in REGION, s in
STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y in YEAR}: if ld > min{ldld in DAYTYPE}
min(ldld) then (StorageLevelDayTypeFinish[r,s,ls,ld-1,y]+sum{lhlh in DAILYTIMEBRACKET:lh-lhlh>0} (((sum{t in
TECHNOLOGY, m in MODE_OF_OPERATION, l in TIMESLICE:TechnologyToStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] *
TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh]) - (sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION, l in TIMESLICE:TechnologyFromStorage[r,t,s,m]>0} RateOfActivity[r,l,t,m,y] *
TechnologyFromStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh])) * DaySplit[lh,y]))-(sum{yy in
YEAR: y-yy < OperationalLifeStorage[r,s] && y-yy>=0} NewStorageCapacity[r,s,yy]+ResidualStorageCapacity[r,s,y]) <= 0;

s.t. SC5_MaxChargeConstraint{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET, y
in YEAR}: sum{t in TECHNOLOGY, m in MODE_OF_OPERATION, l in TIMESLICE:TechnologyToStorage[r,t,s,m]>0}
RateOfActivity[r,l,t,m,y] * TechnologyToStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh] <=
StorageMaxChargeRate[r,s];

s.t. SC6_MaxDischargeConstraint{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, lh in DAILYTIMEBRACKET,
y in YEAR}: sum{t in TECHNOLOGY, m in MODE_OF_OPERATION, l in TIMESLICE:TechnologyFromStorage[r,t,s,m]>0}
RateOfActivity[r,l,t,m,y] * TechnologyFromStorage[r,t,s,m] * Conversionls[l,ls] * Conversionld[l,ld] * Conversionlh[l,lh] <=
StorageMaxDischargeRate[r,s];

s.t. SC7_MinStorageLevelDayTypeStartConstraint{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, y in YEAR}:
StorageLevelDayTypeStart [r,s,ls,ld,y] <=  ResidualStorageCapacity[r,s,y];

s.t. SC8_MinStorageLevelDayTypeFinishConstraint{r in REGION, s in STORAGE, ls in SEASON, ld in DAYTYPE, y in YEAR}:
StorageLevelDayTypeFinish [r,s,ls,ld,y] <=  ResidualStorageCapacity[r,s,y];

#########                         Storage Investments                         #############
s.t. SI6_SalvageValueStorageAtEndOfPeriod1{r in REGION, s in STORAGE, y in YEAR: (y+OperationalLifeStorage[r,s]-1) <=
(max{yy in YEAR} max(yy))}: 0 = SalvageValueStorage[r,s,y];

#s.t. SI7_SalvageValueStorageAtEndOfPeriod2{r in REGION, s in STORAGE, y in YEAR: (DepreciationMethod[r]=1 &&
(y+OperationalLifeStorage[r,s]-1) > (max{yy in YEAR} max(yy)) && DiscountRateStorage[r,s]=0) || (DepreciationMethod[r]=2
&& (y+OperationalLifeStorage[r,s]-1) > (max{yy in YEAR} max(yy)))}: CapitalCostStorage[r,s,y] *
NewStorageCapacity[r,s,y]*(1-(max{yy in YEAR} max(yy) - y+1)/OperationalLifeStorage[r,s]) = SalvageValueStorage[r,s,y];

#s.t. SI8_SalvageValueStorageAtEndOfPeriod3{r in REGION, s in STORAGE, y in YEAR: DepreciationMethod[r]=1 &&
(y+OperationalLifeStorage[r,s]-1) > (max{yy in YEAR} max(yy)) && DiscountRateStorage[r,s]>0}: CapitalCostStorage[r,s,y] *
NewStorageCapacity[r,s,y]*(1-(((1+DiscountRateStorage[r,s])^(max{yy in YEAR} max(yy) - y+1)-
1)/((1+DiscountRateStorage[r,s])^OperationalLifeStorage[r,s]-1))) = SalvageValueStorage[r,s,y];

#s.t. SI1_StorageUpperLimit{r in REGION, s in STORAGE, y in YEAR}: sum{yy in YEAR: y-yy < OperationalLifeStorage[r,s]
&& y-yy>=0} NewStorageCapacity[r,s,yy]+ResidualStorageCapacity[r,s,y] = StorageUpperLimit[r,s,y];
#s.t. SI2_StorageLowerLimit{r in REGION, s in STORAGE, y in YEAR}: MinStorageCharge[r,s,y]*(sum{yy in YEAR: y-yy <
OperationalLifeStorage[r,s] && y-yy>=0} NewStorageCapacity[r,s,yy]+ResidualStorageCapacity[r,s,y]) =
StorageLowerLimit[r,s,y];

#s.t. SI3_TotalNewStorage{r in REGION, s in STORAGE, y in YEAR}: sum{yy in YEAR: y-yy < OperationalLifeStorage[r,s] &&
y-yy>=0} NewStorageCapacity[r,s,yy]=AccumulatedNewStorageCapacity[r,s,y];

#s.t. SI4_UndiscountedCapitalInvestmentStorage{r in REGION, s in STORAGE, y in YEAR}: CapitalCostStorage[r,s,y] *
NewStorageCapacity[r,s,y] = CapitalInvestmentStorage[r,s,y];
```

```
#s.t. SI5_DiscountingCapitalInvestmentStorage{r in REGION, s in STORAGE, y in YEAR}: CapitalCostStorage[r,s,y] *
NewStorageCapacity[r,s,y]/((1+DiscountRateStorage[r,s])^(y-min{yy in YEAR} min(yy))) =
DiscountedCapitalInvestmentStorage[r,s,y];

#s.t. SI9_SalvageValueStorageDiscountedToStartYear{r in REGION, s in STORAGE, y in YEAR}:
SalvageValueStorage[r,s,y]/((1+DiscountRateStorage[r,s])^(max{yy in YEAR} max(yy)-min{yy in YEAR} min(yy)+1)) =
DiscountedSalvageValueStorage[r,s,y];

#s.t. SI10_TotalDiscountedCostByStorage{r in REGION, s in STORAGE, y in YEAR}: (CapitalCostStorage[r,s,y] *
NewStorageCapacity[r,s,y]/((1+DiscountRateStorage[r,s])^(y-min{yy in YEAR} min(yy)))-CapitalCostStorage[r,s,y] *
NewStorageCapacity[r,s,y]/((1+DiscountRateStorage[r,s])^(y-min{yy in YEAR} min(yy)))) = TotalDiscountedStorageCost[r,s,y];

#########          Capital Costs                    #############
#s.t. CC1_UndiscountedCapitalInvestment{r in REGION, t in TECHNOLOGY, y in YEAR}: CapitalCost[r,t,y] *
NewCapacity[r,t,y] = CapitalInvestment[r,t,y];
####s.t. CC2_DiscountingCapitalInvestment{r in REGION, t in TECHNOLOGY, y in YEAR}: CapitalCost[r,t,y] *
NewCapacity[r,t,y]/((1+DiscountRate[r,t])^(y-min{yy in YEAR} min(yy))) = DiscountedCapitalInvestment[r,t,y];

#########       Salvage Value          #############
s.t. SV1_SalvageValueAtEndOfPeriod1{r in REGION, t in TECHNOLOGY, y in YEAR: (y + OperationalLife[r,t]-1) > (max{yy in
YEAR} max(yy)) && DiscountRate[r,t]>0}: SalvageValue[r,t,y] = CapitalCost[r,t,y]*NewCapacity[r,t,y]*(1-
(((1+DiscountRate[r,t])^(max{yy in YEAR} max(yy) - y+1)-1)/((1+DiscountRate[r,t])^OperationalLife[r,t]-1)));

s.t. SV2_SalvageValueAtEndOfPeriod2{r in REGION, t in TECHNOLOGY, y in YEAR: (y + OperationalLife[r,t]-1) > (max{yy in
YEAR} max(yy)) && DiscountRate[r,t]=0}: SalvageValue[r,t,y] = CapitalCost[r,t,y]*NewCapacity[r,t,y]*(1-(max{yy in YEAR}
max(yy) - y+1)/OperationalLife[r,t]);

s.t. SV3_SalvageValueAtEndOfPeriod3{r in REGION, t in TECHNOLOGY, y in YEAR: (y + OperationalLife[r,t]-1) <= (max{yy
in YEAR} max(yy))}: SalvageValue[r,t,y] = 0;

s.t. SV4_SalvageValueDiscountedToStartYear{r in REGION, t in TECHNOLOGY, y in YEAR}: DiscountedSalvageValue[r,t,y] =
SalvageValue[r,t,y]/((1+DiscountRate[r,t])^(1+max{yy in YEAR} max(yy)-min{yy in YEAR} min(yy)));

#########          Operating Costs                  #############

#s.t. OC1_OperatingCostsVariable{r in REGION, t in TECHNOLOGY, y in YEAR}: sum{m in MODE_OF_OPERATION, l in
TIMESLICE} RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*VariableCost[r,t,m,y] = AnnualVariableOperatingCost[r,t,y];

#s.t. OC2_OperatingCostsFixedAnnual{r in REGION, t in TECHNOLOGY, y in YEAR}: ((sum{yy in YEAR: y-yy <
OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y])*FixedCost[r,t,y] =
AnnualFixedOperatingCost[r,t,y];

#s.t. OC3_OperatingCostsTotalAnnual{r in REGION, t in TECHNOLOGY, y in YEAR}: (((sum{yy in YEAR: y-yy <
OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y])*FixedCost[r,t,y] + sum{m in
MODE_OF_OPERATION, l in TIMESLICE} RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*VariableCost[r,t,m,y]) =
OperatingCost[r,t,y];

####s.t. OC4_DiscountedOperatingCostsTotalAnnual{r in REGION, t in TECHNOLOGY, y in YEAR}: (((sum{yy in YEAR: y-yy
< OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y])*FixedCost[r,t,y] + sum{m in
MODE_OF_OPERATION, l in TIMESLICE}
```

```
RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*VariableCost[r,t,m,y])/((1+DiscountRate[r,t])^(y-min{yy in YEAR} min(yy)+0.5)) =
DiscountedOperatingCost[r,t,y];

#########          Total Discounted Costs                    #############
#s.t. TDC1_TotalDiscountedCostByTechnology{r in REGION, t in TECHNOLOGY, y in YEAR}: ((((sum{yy in YEAR: y-yy <
OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y])*FixedCost[r,t,y] + sum{m in
MODE_OF_OPERATION, l in TIMESLICE}
RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*VariableCost[r,t,m,y])/((1+DiscountRate[r,t])^(y-min{yy in YEAR}
min(yy)+0.5))+CapitalCost[r,t,y] * NewCapacity[r,t,y]/((1+DiscountRate[r,t])^(y-min{yy in YEAR}
min(yy)))+DiscountedTechnologyEmissionsPenalty[r,t,y]-DiscountedSalvageValue[r,t,y]) =
TotalDiscountedCostByTechnology[r,t,y];

####s.t. TDC2_TotalDiscountedCost{r in REGION, y in YEAR}: sum{t in TECHNOLOGY}((((sum{yy in YEAR: y-yy <
OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y])*FixedCost[r,t,y] + sum{m in
MODE_OF_OPERATION, l in TIMESLICE}
RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*VariableCost[r,t,m,y])/((1+DiscountRate[r,t])^(y-min{yy in YEAR}
min(yy)+0.5))+CapitalCost[r,t,y] * NewCapacity[r,t,y]/((1+DiscountRate[r,t])^(y-min{yy in YEAR}
min(yy)))+DiscountedTechnologyEmissionsPenalty[r,t,y]-DiscountedSalvageValue[r,t,y]) + sum{s in STORAGE}
(CapitalCostStorage[r,s,y] * NewStorageCapacity[r,s,y]/((1+DiscountRateStorage[r,s])^(y-min{yy in YEAR} min(yy)))-
CapitalCostStorage[r,s,y] * NewStorageCapacity[r,s,y]/((1+DiscountRateStorage[r,s])^(y-min{yy in YEAR} min(yy)))) =
TotalDiscountedCost[r,y];

#########                    Total Capacity Constraints        ##############
s.t. TCC1_TotalAnnualMaxCapacityConstraint{r in REGION, t in TECHNOLOGY, y in YEAR}: ((sum{yy in YEAR: y-yy <
OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y]) <= TotalAnnualMaxCapacity[r,t,y];

s.t. TCC2_TotalAnnualMinCapacityConstraint{r in REGION, t in TECHNOLOGY, y in YEAR:
TotalAnnualMinCapacity[r,t,y]>0}: ((sum{yy in YEAR: y-yy < OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+
ResidualCapacity[r,t,y]) >= TotalAnnualMinCapacity[r,t,y];

#########                    New Capacity Constraints          ##############
s.t. NCC1_TotalAnnualMaxNewCapacityConstraint{r in REGION, t in TECHNOLOGY, y in YEAR}: NewCapacity[r,t,y] <=
TotalAnnualMaxCapacityInvestment[r,t,y];

s.t. NCC2_TotalAnnualMinNewCapacityConstraint{r in REGION, t in TECHNOLOGY, y in YEAR:
TotalAnnualMinCapacityInvestment[r,t,y]>0}: NewCapacity[r,t,y] >= TotalAnnualMinCapacityInvestment[r,t,y];

#########                    Annual Activity Constraints       ##############
s.t. AAC2_TotalAnnualTechnologyActivityUpperLimit{r in REGION, t in TECHNOLOGY, y in YEAR}: sum{l in TIMESLICE,
m in MODE_OF_OPERATION} RateOfActivity[r,l,t,m,y]*YearSplit[l,y] <= TotalTechnologyAnnualActivityUpperLimit[r,t,y] ;

s.t. AAC3_TotalAnnualTechnologyActivityLowerLimit{r in REGION, t in TECHNOLOGY, y in YEAR:
TotalTechnologyAnnualActivityLowerLimit[r,t,y]>0}: sum{l in TIMESLICE, m in MODE_OF_OPERATION}
RateOfActivity[r,l,t,m,y]*YearSplit[l,y] >= TotalTechnologyAnnualActivityLowerLimit[r,t,y] ;

s.t. AAC1_TotalAnnualTechnologyActivity{r in REGION, t in TECHNOLOGY, y in YEAR}: sum{l in TIMESLICE, m in
MODE_OF_OPERATION} RateOfActivity[r,l,t,m,y]*YearSplit[l,y] = TotalTechnologyAnnualActivity[r,t,y];

#s.t. AAC4_MinElecGeneration{r in REGION, t in TECHNOLOGY, l in TIMESLICE, y in YEAR}: TotalCapacityAnnual[r,t,y] *
CapacityToActivityUnit[r,t] * MinElecGeneration[r,t,l,y] <= RateOfTotalActivity[r,t,l,y];
```

```
#s.t. AAC5_MinElecGeneration{r in REGION, t in TECHNOLOGY, l in TIMESLICE, y in YEAR:
MinGenerationTagTechonology[r,t]=1}: TotalCapacityAnnual[r,t,y] * CapacityToActivityUnit[r,t] * MinElecGeneration[r,t,l,y] <=
RateOfTotalActivity[r,t,l,y];

s.t. AAC6_TotalAnnualMinElecGeneration{r in REGION, t in TECHNOLOGY, y in YEAR:
MinGenerationTagTechonology[r,t]=1}: TotalCapacityAnnual[r,t,y] * CapacityToActivityUnit[r,t] * MinElecGeneration[r,t,y] <=
TotalTechnologyAnnualActivity[r,t,y];

#########                    Total Activity Constraints          ##############
s.t. TAC2_TotalModelHorizonTechnologyActivityUpperLimit{r in REGION, t in TECHNOLOGY}: sum{l in TIMESLICE, m in
MODE_OF_OPERATION, y in YEAR} RateOfActivity[r,l,t,m,y]*YearSplit[l,y] <=
TotalTechnologyModelPeriodActivityUpperLimit[r,t] ;

s.t. TAC3_TotalModelHorizenTechnologyActivityLowerLimit{r in REGION, t in TECHNOLOGY:
TotalTechnologyModelPeriodActivityLowerLimit[r,t]>0}: sum{l in TIMESLICE, m in MODE_OF_OPERATION, y in YEAR}
RateOfActivity[r,l,t,m,y]*YearSplit[l,y] >= TotalTechnologyModelPeriodActivityLowerLimit[r,t] ;

#s.t. TAC1_TotalModelHorizonTechnologyActivity{r in REGION, t in TECHNOLOGY}: sum{l in TIMESLICE, m in
MODE_OF_OPERATION, y in YEAR} RateOfActivity[r,l,t,m,y]*YearSplit[l,y] = TotalTechnologyModelPeriodActivity[r,t];

#########                    Reserve Margin Constraint          ##############
#s.t. RM3_ReserveMargin_Constraint{r in REGION, l in TIMESLICE, y in YEAR}: sum{m in MODE_OF_OPERATION, t in
TECHNOLOGY, f in FUEL: OutputActivityRatio[r,t,f,m,y] <>0} RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y] *
ReserveMarginTagFuel[r,f,y] * ReserveMargin[r,y]<= sum {t in TECHNOLOGY} ((sum{yy in YEAR: y-yy < OperationalLife[r,t]
&& y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y]) * ReserveMarginTagTechnology[r,t,y] *
CapacityToActivityUnit[r,t];

#s.t. RM1_ReserveMargin_TechologiesIncluded_In_Activity_Units{r in REGION, l in TIMESLICE, y in YEAR}: sum {t in
TECHNOLOGY} ((sum{yy in YEAR: y-yy < OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y]) *
ReserveMarginTagTechnology[r,t,y] * CapacityToActivityUnit[r,t]          =          TotalCapacityInReserveMargin[r,y];

#s.t. RM2_ReserveMargin_FuelsIncluded{r in REGION, l in TIMESLICE, y in YEAR}:  sum{m in MODE_OF_OPERATION, t in
TECHNOLOGY, f in FUEL: OutputActivityRatio[r,t,f,m,y] <>0} RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y] *
ReserveMarginTagFuel[r,f,y] = DemandNeedingReserveMargin[r,l,y];

#########        SAMBA MARGIN CONSTRAINTS  ##########
s.t. NRM1_ReserMargin_Constraint{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR}:  sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION: OutputActivityRatio[r,t,f,m,y] <>0} RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y] *
ReserveMarginTagFuel[r,f,y] * ReserveMargin[r,f,y] <= sum {m in MODE_OF_OPERATION, t in TECHNOLOGY:
OutputActivityRatio[r,t,f,m,y] <>0} ((sum{yy in YEAR: y-yy < OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+
ResidualCapacity[r,t,y]) * ReserveMarginTagTechnology[r,t,y] * CapacityToActivityUnit[r,t];

#########                    RE Production Target          ############## NTS: Should change demand for production
#s.t. RE4_EnergyConstraint{r in REGION, y in YEAR}:REMinProductionTarget[r,y]*sum{l in TIMESLICE, f in FUEL}
SpecifiedAnnualDemand[r,f,y]*SpecifiedDemandProfile[r,f,l,y]*RETagFuel[r,f,y] <= sum{m in MODE_OF_OPERATION, l in
TIMESLICE, t in TECHNOLOGY, f in FUEL: OutputActivityRatio[r,t,f,m,y] <>0}
RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y] * YearSplit[l,y]*RETagTechnology[r,t,y];
#s.t. RE1_FuelProductionByTechnologyAnnual{r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR}: sum{m in
MODE_OF_OPERATION, l in TIMESLICE: OutputActivityRatio[r,t,f,m,y] <>0}
RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y] * YearSplit[l,y] = ProductionByTechnologyAnnual[r,t,f,y];
```

```
#s.t. RE2_TechIncluded{r in REGION, y in YEAR}: sum{m in MODE_OF_OPERATION, l in TIMESLICE, t in TECHNOLOGY,
f in FUEL: OutputActivityRatio[r,t,f,m,y] <>0} RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y] *
YearSplit[l,y]*RETagTechnology[r,t,y] = TotalREProductionAnnual[r,y];

#s.t. RE3_FuelIncluded{r in REGION, y in YEAR}: sum{l in TIMESLICE, f in FUEL}
SpecifiedAnnualDemand[r,f,y]*SpecifiedDemandProfile[r,f,l,y]*RETagFuel[r,f,y] = RETotalDemandOfTargetFuelAnnual[r,y];

#s.t. RE5_FuelUseByTechnologyAnnual{r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR}: sum{m in
MODE_OF_OPERATION, l in TIMESLICE: InputActivityRatio[r,t,f,m,y]<>0}
RateOfActivity[r,l,t,m,y]*InputActivityRatio[r,t,f,m,y]*YearSplit[l,y] = UseByTechnologyAnnual[r,t,f,y];

#########                    Emissions Accounting                    ##############
#s.t. E5_DiscountedEmissionsPenaltyByTechnology{r in REGION, t in TECHNOLOGY, y in YEAR}: sum{e in EMISSION, l in
TIMESLICE, m in MODE_OF_OPERATION: EmissionActivityRatio[r,t,e,m,y]<>0}
EmissionActivityRatio[r,t,e,m,y]*RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*EmissionsPenalty[r,e,y]/((1+DiscountRate[r,t])^(y-
min{yy in YEAR} min(yy)+0.5)) = DiscountedTechnologyEmissionsPenalty[r,t,y];

s.t. E8_AnnualEmissionsLimit{r in REGION, e in EMISSION, y in YEAR}: sum{l in TIMESLICE, t in TECHNOLOGY, m in
MODE_OF_OPERATION: EmissionActivityRatio[r,t,e,m,y]<>0}
EmissionActivityRatio[r,t,e,m,y]*RateOfActivity[r,l,t,m,y]*YearSplit[l,y]+AnnualExogenousEmission[r,e,y] <=
AnnualEmissionLimit[r,e,y];

#s.t. E9_ModelPeriodEmissionsLimit{r in REGION, e in EMISSION}:  sum{l in TIMESLICE, t in TECHNOLOGY, m in
MODE_OF_OPERATION, y in YEAR: EmissionActivityRatio[r,t,e,m,y]<>0}
EmissionActivityRatio[r,t,e,m,y]*RateOfActivity[r,l,t,m,y]*YearSplit[l,y] + ModelPeriodExogenousEmission[r,e] <=
ModelPeriodEmissionLimit[r,e] ;

#s.t. E1_AnnualEmissionProductionByMode{r in REGION, t in TECHNOLOGY, e in EMISSION, m in
MODE_OF_OPERATION, y in YEAR}: EmissionActivityRatio[r,t,e,m,y]*sum{l in TIMESLICE}
RateOfActivity[r,l,t,m,y]*YearSplit[l,y]=AnnualTechnologyEmissionByMode[r,t,e,m,y];

#s.t. E2_AnnualEmissionProduction{r in REGION, t in TECHNOLOGY, e in EMISSION, m in MODE_OF_OPERATION, y in
YEAR: EmissionActivityRatio[r,t,e,m,y]<>0}: sum{l in TIMESLICE, m in MODE_OF_OPERATION}
EmissionActivityRatio[r,t,e,m,y]*RateOfActivity[r,l,t,m,y]*YearSplit[l,y] = AnnualTechnologyEmission[r,t,e,y];

#s.t. E3_EmissionsPenaltyByTechAndEmission{r in REGION, t in TECHNOLOGY, e in EMISSION, y in YEAR:
EmissionActivityRatio[r,t,e,m,y]<>0}: sum{l in TIMESLICE, m in MODE_OF_OPERATION}
EmissionActivityRatio[r,t,e,m,y]*RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*EmissionsPenalty[r,e,y] =
AnnualTechnologyEmissionPenaltyByEmission[r,t,e,y];

#s.t. E4_EmissionsPenaltyByTechnology{r in REGION, t in TECHNOLOGY, y in YEAR}: sum{e in EMISSION, l in
TIMESLICE, m in MODE_OF_OPERATION}
EmissionActivityRatio[r,t,e,m,y]*RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*EmissionsPenalty[r,e,y] =
AnnualTechnologyEmissionsPenalty[r,t,y];

#s.t. E6_EmissionsAccounting1{r in REGION, e in EMISSION, y in YEAR: EmissionActivityRatio[r,t,e,m,y]<>0}: sum{l in
TIMESLICE, t in TECHNOLOGY, m in MODE_OF_OPERATION}
EmissionActivityRatio[r,t,e,m,y]*RateOfActivity[r,l,t,m,y]*YearSplit[l,y] = AnnualEmissions[r,e,y];

#s.t. E7_EmissionsAccounting2{r in REGION, e in EMISSION: EmissionActivityRatio[r,t,e,m,y]<>0}: sum{l in TIMESLICE, t in
TECHNOLOGY, m in MODE_OF_OPERATION, y in YEAR}
```

```
EmissionActivityRatio[r,t,e,m,y]*RateOfActivity[r,l,t,m,y]*YearSplit[l,y] + ModelPeriodExogenousEmission[r,e] = ModelPeriodEmissions[r,e];

#########                    SAMBA OUTPUT VARIABLES                    ##############
s.t. V1_TotalCost{r in REGION}: sum{t in TECHNOLOGY, y in YEAR}(((((sum{yy in YEAR: y-yy < OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y])*FixedCost[r,t,y] + sum{m in MODE_OF_OPERATION, l in TIMESLICE} RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*VariableCost[r,t,m,y])/((1+DiscountRate[r,t])^(y-min{yy in YEAR} min(yy)+0.5))+CapitalCost[r,t,y] * NewCapacity[r,t,y]/((1+DiscountRate[r,t])^(y-min{yy in YEAR} min(yy)))-DiscountedSalvageValue[r,t,y]) + sum{s in STORAGE} (CapitalCostStorage[r,s,y] * NewStorageCapacity[r,s,y]/((1+DiscountRateStorage[r,s])^(y-min{yy in YEAR} min(yy)))-CapitalCostStorage[r,s,y] * NewStorageCapacity[r,s,y]/((1+DiscountRateStorage[r,s])^(y-min{yy in YEAR} min(yy))))) = ModelPeriodCostByRegion[r];

#s.t. V2_DemandByTimeSlice{r in REGION, f in FUEL, l in TIMESLICE, y in YEAR}: SpecifiedAnnualDemand[r,f,y]*SpecifiedDemandProfile[r,f,l,y] = DemandByTimeSlice[r,f,l,y];

#s.t. V3_FuelProductionByTimeSlice{r in REGION, f in FUEL, l in TIMESLICE, y in YEAR}: sum{m in MODE_OF_OPERATION, t in TECHNOLOGY: OutputActivityRatio[r,t,f,m,y] <>0} RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y]*YearSplit[l,y] = FuelProductionByTimeSlice[r,f,l,y];

s.t. V4_TotalAnnualCapacity{r in REGION, t in TECHNOLOGY, y in YEAR}: ((sum{yy in YEAR: y-yy < OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y])  = TotalAnnualCapacity[r,t,y];

s.t. V5_AnnualProductionByTechnology{r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR}: sum{m in MODE_OF_OPERATION, l in TIMESLICE: OutputActivityRatio[r,t,f,m,y] <>0} RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y] * YearSplit[l,y] = AnnualProductionByTechnology[r,t,f,y];

s.t. V6_AnnualUseByTechnology{r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR}: sum{m in MODE_OF_OPERATION, l in TIMESLICE: InputActivityRatio[r,t,f,m,y]<>0} RateOfActivity[r,l,t,m,y]*InputActivityRatio[r,t,f,m,y]*YearSplit[l,y] = AnnualUseByTechnology[r,t,f,y];

#s.t. V7_ProductionByTechnologyByTimeSlice{r in REGION, t in TECHNOLOGY, f in FUEL, l in TIMESLICE, y in YEAR}: sum{m in MODE_OF_OPERATION: OutputActivityRatio[r,t,f,m,y] <>0} RateOfActivity[r,l,t,m,y]*OutputActivityRatio[r,t,f,m,y] * YearSplit[l,y] = ProductionByTechnologyByTimeSlice[r,t,f,l,y];

#s.t. V8_UseByTechnologyByTimeSlice{r in REGION, t in TECHNOLOGY, f in FUEL, l in TIMESLICE, y in YEAR}: sum{m in MODE_OF_OPERATION: InputActivityRatio[r,t,f,m,y]<>0} RateOfActivity[r,l,t,m,y]*InputActivityRatio[r,t,f,m,y] * YearSplit[l,y] = UseByTechnologyByTimeSlice[r,t,f,l,y];

s.t. V9_AnnualEmissions{r in REGION, e in EMISSION, y in YEAR}: sum{l in TIMESLICE, t in TECHNOLOGY, m in MODE_OF_OPERATION} EmissionActivityRatio[r,t,e,m,y]*RateOfActivity[r,l,t,m,y]*YearSplit[l,y] = AnnualEmissions[r,e,y];

#s.t. V10_AnnualEmissionsByTechnology{r in REGION, t in TECHNOLOGY, e in EMISSION, y in YEAR}: sum{l in TIMESLICE, m in MODE_OF_OPERATION} EmissionActivityRatio[r,t,e,m,y]*RateOfActivity[r,l,t,m,y]*YearSplit[l,y] = AnnualEmissionsByTechnology[r,t,e,y];

s.t. CC1_UndiscountedCapitalInvestment{r in REGION, t in TECHNOLOGY, y in YEAR}: CapitalCost[r,t,y] * NewCapacity[r,t,y] = CapitalInvestment[r,t,y];

s.t. CC2_DiscountedCapitalInvestment{r in REGION, t in TECHNOLOGY, y in YEAR}: CapitalCost[r,t,y] * NewCapacity[r,t,y]/((1+DiscountRate[r,t])^(y-min{yy in YEAR} min(yy))) = DiscountedCapitalInvestment[r,t,y];
```

```
s.t. TDC1_TotalDiscountedCostByTechnology{r in REGION, t in TECHNOLOGY, y in YEAR}: ((((sum{yy in YEAR: y-yy <
OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y])*FixedCost[r,t,y] + sum{m in
MODE_OF_OPERATION, l in TIMESLICE}
RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*VariableCost[r,t,m,y])/((1+DiscountRate[r,t])^(y-min{yy in YEAR}
min(yy)+0.5))+CapitalCost[r,t,y] * NewCapacity[r,t,y]/((1+DiscountRate[r,t])^(y-min{yy in YEAR} min(yy)))-
DiscountedSalvageValue[r,t,y]) = TotalDiscountedCostByTechnology[r,t,y];

s.t. TDC2_TotalDiscountedCost{r in REGION, y in YEAR}: sum{t in TECHNOLOGY}((((sum{yy in YEAR: y-yy <
OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y])*FixedCost[r,t,y] + sum{m in
MODE_OF_OPERATION, l in TIMESLICE}
RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*VariableCost[r,t,m,y])/((1+DiscountRate[r,t])^(y-min{yy in YEAR}
min(yy)+0.5))+CapitalCost[r,t,y] * NewCapacity[r,t,y]/((1+DiscountRate[r,t])^(y-min{yy in YEAR} min(yy)))-
DiscountedSalvageValue[r,t,y]) + sum{s in STORAGE} (CapitalCostStorage[r,s,y] *
NewStorageCapacity[r,s,y]/((1+DiscountRateStorage[r,s])^(y-min{yy in YEAR} min(yy)))-CapitalCostStorage[r,s,y] *
NewStorageCapacity[r,s,y]/((1+DiscountRateStorage[r,s])^(y-min{yy in YEAR} min(yy)))) = TotalDiscountedCost[r,y];

s.t. OC1_OperatingCostsVariable{r in REGION, t in TECHNOLOGY, y in YEAR}: sum{m in MODE_OF_OPERATION, l in
TIMESLICE} RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*VariableCost[r,t,m,y] = AnnualVariableOperatingCost[r,t,y];

s.t. OC2_OperatingCostsFixedAnnual{r in REGION, t in TECHNOLOGY, y in YEAR}: ((sum{yy in YEAR: y-yy <
OperationalLife[r,t] && y-yy>=0} NewCapacity[r,t,yy])+ ResidualCapacity[r,t,y])*FixedCost[r,t,y] =
AnnualFixedOperatingCost[r,t,y];

#s.t. E4_EmissionsPenaltyByTechnology{r in REGION, t in TECHNOLOGY, y in YEAR}: sum{e in EMISSION, l in
TIMESLICE, m in MODE_OF_OPERATION}
EmissionActivityRatio[r,t,e,m,y]*RateOfActivity[r,l,t,m,y]*YearSplit[l,y]*EmissionsPenalty[r,e,y] =
AnnualTechnologyEmissionsPenalty[r,t,y];

s.t. RC1_WBResidualCap{r in REGION, t in TECHNOLOGY, y in YEAR}: ResidualCapacity[r,t,y] = WBResidualCapacity[r,t,y];
###############################################################################################
solve;
end;
```

Apêndice (Appendix) B – Shapley Value calculations using Frank Algorithm in Scilab

```
// The following function return all combinations of n taken m by m
// For example, n=3, m=2, then
// A = [[1 2], [1 3], [2 3]]

function [A] = all_comb(n,m)
    ncT = factorial(n)/(factorial(m)*factorial(n-m))
    A(ncT,m) = 0;
    for j = 1:m
        k=j;
        i0=1;
        while i0<=ncT
            n0 = n-k; m0 = m-j;
            i1 = i0-1 + factorial(n0)/(factorial(m0)*factorial(n0-m0));
            A(i0:i1,j)=k;
            if(n-k == m-j & i0<ncT) then
                k = A(i1+1,j-1)+1;
            else
                k=k+1;
            end
            i0=i1+1;
        end
    end
endfunction

n = 6
m = 1

while m<(n+1) do
    comb = all_comb(n,m);
    disp (comb)
    m=m+1;
end
if comb(1)== 1 then
    comb(1)== "Brasil"
    disp(comb(1))
end

// Matriz (1024 x 12)
//----------------------------------------
paises = zeros (3, 21);
for n = 1:1:21
printf("Linha %g:\n", n)
    paises(1, n) = input("Primeiro pais (Numeral menor): ");
    paises(2, n) = input("Segundo pais (Numeral maior): ");
    paises(3, n) = input("Valor da coalizão: ")


    printf("\n");
    end


for LIN = 1:1:1024;
    soma = 0
    vetorsoma = zeros(1, 21)
    for COL = 1:1:11;

    if COL == 1 then
        A = COL + 1
B = A + 1
C = B + 1
D = C + 1
E = D + 1
F = E + 1
G = F + 1
H = G + 1
I = H + 1
J = I + 1
K=12
end
```

```
if COL == 2 then A = COL + 1
B = A + 1
C = B + 1
D = C + 1
E = D + 1
F = E + 1
G = F + 1
H = G + 1
I = H + 1
J = 12
K=12
end
if COL == 3 then A = COL + 1
B = A + 1
C = B + 1
D = C + 1
E = D + 1
F = E + 1
G = F + 1
H = G + 1
I = 12
J = 12
K=12
end
if COL == 4 then A = COL + 1
B = A + 1
C = B + 1
D = C + 1
E = D + 1
F = E + 1
G = F + 1
H = 12
I = 12
J = 12
K=12
end
if COL == 5 then A = COL + 1
B = A + 1
C = B + 1
D = C + 1
E = D + 1
F = E + 1
G = 12
H = 12
I = 12
J = 12
K=12
end
if COL == 6 then A = COL + 1
B = A + 1
C = B + 1
D = C + 1
E = D + 1
F = 12
G = 12
H = 12
I = 12
J = 12
K=12
end
if COL == 7 then A = COL + 1
B = A + 1
C = B + 1
D = C + 1
E = 12
F = 12
G = 12
H = 12
I = 12
J = 12
K=12
end
if COL == 8 then A = COL + 1
B = A + 1
C = B + 1
D = 12
```

```
E = 12
F = 12
G = 12
H = 12
I = 12
J = 12
K=12
end
if COL == 9 then A = COL + 1
B = A + 1
C = 12
D = 12
E = 12
F = 12
G = 12
H = 12
I = 12
J = 12
K=12
end
if COL == 10 then A = COL + 1
B = 12
C = 12
D = 12
E = 12
F = 12
G = 12
H = 12
I = 12
J = 12
K=12
end
if COL == 11 then A = 12
B = 12
C = 12
D = 12
E = 12
F = 12
G = 12
H = 12
I = 12
J = 12
K=12
end

    for z = 1:1:21

    if M(LIN, COL)== paises(1, z) & M(LIN, A)== paises(2, z) then
 soma = soma + paises(3, z)
    end
if M(LIN, COL)==paises(1, z) & M(LIN, B)== paises(2, z) then
 soma = soma + paises(3, z)
 end
 if M(LIN, COL)==paises(1, z) & M(LIN, C)== paises(2, z) then
 soma = soma + paises(3, z)
 end
 if M(LIN, COL)==paises(1, z) & M(LIN, D)== paises(2, z) then
 soma = soma + paises(3, z)
end
if M(LIN, COL)==paises(1, z) & M(LIN, E)== paises(2, z) then
 soma = soma + paises(3, z)
end
if M(LIN, COL)==paises(1, z) & M(LIN, F)== paises(2, z) then
 soma = soma + paises(3, z)
end
if M(LIN, COL)==paises(1, z) & M(LIN, G)== paises(2, z) then
 soma = soma + paises(3, z)
end
if M(LIN, COL)==paises(1, z) & M(LIN, H)== paises(2, z) then
 soma = soma + paises(3, z)
end
if M(LIN, COL)==paises(1, z) & M(LIN, I)== paises(2, z) then
 soma = soma + paises(3, z)
end
if M(LIN, COL)==paises(1, z) & M(LIN, J)== paises(2, z) then
 soma = soma + paises(3, z)
```

```
end
if M(LIN, COL)==paises(1, z) & M(LIN, K)== paises(2, z) then
 soma = soma + paises(3, z)
end
// ARMAZENAMENTO DA SOMA
vetorsoma(1, n) = soma
        end
        sum(vetorsoma)
        soma = ans

    end
          //printf (" Na linha: %g Valor da coalizão: ", LIN);
       printf ("%g \n", soma);
                    end
```

Apêndice (Appendix) C – National and international power sector data sources

Data was gathered from a great number of sources: monthly and annual reports of sectorial institutions; national expansion plans from energy ministries, state owned or private companies; and International organization reports. In addition, an extensive bibliographical search was carried out to identify power sector features of eleven countries: Argentina (MPF, 2013; CNEA, 2015a; CNEA, 2015b; CAMMESA, 2015a; CAMMESA, 2015b), Bolivia (AE, 2012a; AE, 2012b; AE, 2013; MHE, 2014), Brazil (EPE, 2012; EPE, 2013; EPE, 2014a; EPE, 2014b; EPE, 2015a; EPE, 2015b; ONS, 2014; ONS, 2015a; MME, 2006; MME, 2014), Chile (CDEC SING, 2012; CDEC SIC, 2013; MEN, 2014; MEN, 2015); Colombia (MME, 2011; UPME, 2013; SIEL, 2015); Ecuador (MEER, 2012; CONELEC, 2013; ARCONEL, 2014a; ARCONEL, 2014b); Guyana (GPL, 2012); Paraguay (ANDE, 2015; VMME, 2014; VMME, 2015); Peru (MEM, 2014; COES SINAC, 2013; COES SINAC, 2015); Uruguay (DNE, 2013; ADME, 2015a; ADME, 2015b) and Venezuela (CNG, 2008; MPPEE, 2013a; MPPEE, 2013b; MPPEE, 2014; CORPOELEC, 2015). Suriname power system was not included in SAMBA scenarios since no international power project has been identified.

International organization reports also provided important data: Síntesis Informativa Energética de los países da CIER 2013 (CIER, 2013), Panorama General del Sector Eléctrico en América Latina y Caribe (OLADE, 2012), Apuntes Sobre la Integración Elétrica Regional y Propuestas para Avanzar (OLADE, 2013), Potencial de Recursos Energéticos y Minerales em América del Sur (UNASUR, 2013), Agenda de Proyectos Prioritarios de Integración (IIRSA, 2015), World Energy Outlook (WEO) 2014 (IEA WEO, 2014), Energy Technologies Perspectives (ETP) (IEA WEO, 2012; IEA WEO, 2014; IEA WEO, 2015), ETSAP Technology Brief (IEA ETSAP, 2010a; IEA ETSAP, 2010b; IEA ETSAP, 2010c; IEA ETSAP, 2010d; IEA ETSAP, 2010e; IEA ETSAP, 2013a; IEA ETSAP, 2013b; IEA ETSAP, 2014), World Energy Perspective Cost of Energy Technologies (WEC, 2013) and World Bank (Word Bank, 2015). Finally, United States institutions were also an important data source (US EPA, 2014; USGS, 2006; US EIA, 2015).

Apêndice (Appendix) D - Generation Input Data

The life span of each technology modelled in accordance with the Energy Technology Systems Analysis Program (ETSAP) Technology Brief reports (IEA ETSAP, 2010a; IEA ETSAP, 2010b; IEA ETSAP, 2010c; IEA ETSAP, 2010d; IEA ETSAP, 2010e; IEA ETSAP, 2013a; IEA ETSAP, 2013b; IEA ETSAP, 2014). For fossil fuel technologies, the thermal efficiency and its corresponding future improvements were obtained from the Energy Technologies Perspectives report (IEA ETP, 2012; IEA ETP, 2014; IEA ETP, 2015).

The capital costs of each technology were identified from the last three editions of Energy Technologies Perspectives reports (IEA ETP, 2012; IEA ETP, 2014; IEA ETP, 2015) and World Energy Perspectives report (WEC, 2013). Capital costs of transmission lines were obtained from OLADE (2013) and IEA ETSAP (2014). Investment costs were estimated using the capital cost and a discount rate of 8% during the time period required to build each power project. The fixed and variable costs were obtained from (WEC, 2013) and (IEA ETSAP, 2010a; IEA ETSAP, 2010b; IEA ETSAP, 2010c; IEA ETSAP, 2010d; IEA ETSAP, 2010e; IEA ETSAP, 2013a; IEA ETSAP, 2013b; IEA ETSAP, 2014). For strategic hydro projects, the lowest cost available in literature for large hydro was considered. Finally, capital cost reductions over time were applied for each technology according to IEA ETP (2012), IEA ETP (2014) and IEA ETP (2015).

Table D.1

Generation Input Data in 2013

Source: based on (IEA ETSAP, 2010a; IEA ETSAP, 2010b; IEA ETSAP, 2010c; IEA ETSAP, 2010d; IEA ETSAP, 2010e; IEA ETSAP, 2013a; IEA ETSAP, 2013b; IEA ETSAP, 2014; IEA ETP, 2012; IEA ETP, 2014; IEA ETP, 2015).

Technologies	**Investment Cost**	**Fixed Cost**	**Variable Cost**	**Inflexibility (min cap. factor)**	**Capacity Factor^a**	**Efficiency^b**	**Expected lifetime**	**Construction time**
	US$/kW	US$/kW	US$/GJ	% of installed capacity	%	%	Years	Years
Biogas	2449	50	1.8	34	85	40	25	4
Biomass Incineration	1905	13	0.5	34	66	35	25	4
Coal Puverized	3129	44	1	45	85	45	40	4
Coal with CCS	6530	102	1	45	85	40	40	4
Concentrated Solar Power	4914	65	1.7	0	40	35	40	1
Photovoltaics	1944	40	0	0	25	25	25	1
Photovoltaics Distributed	3000	40	0	0	32	25	25	1
Fuel Oil	1400	25	1.7	27	85	35	25	2
Geothermal	3966	120	0	0	85	15	20	2
Hydro Large	2939	45	1	13	na	100	60	5
Hydro Small	3499	35	1	13	na	100	60	2
Hydro Strategic Large	2351	26	0	13	na	100	60	5
Natural Gas Combined Cycle	1260	20	2.5	42	85	57	30	3
Natural Gas Open Cycle	583	10	2.5	27	85	38	30	2
Nuclear (PLWR and PHWR)	7200	115	3.1	50	85	35	40	5
Wind off-shore	4104	114	0	0	42	100	25	1
Wind on-shore	1620	36	0	0	31	100	30	1
Distribution lines	1491	0	0	na	na	75-95	60	1
Transmission lines	746	0	0	na	na	93-96	60	1
Transmission Subsystems	448	0	0	na	na	93-96	60	1

[a] Capacity factor for large, small and strategic large hydro varies across the year during wet and dry seasons in each country

[b] For transmission and distribution lines corresponds to technical and non-technical losses depending on the country

Table D.2

Generation Input Data in 2058

Source: based on (IEA ETSAP, 2010a; IEA ETSAP, 2010b; IEA ETSAP, 2010c; IEA ETSAP, 2010d; IEA ETSAP, 2010e; IEA ETSAP, 2013a; IEA ETSAP, 2013b; IEA ETSAP, 2014; IEA ETP, 2012; IEA ETP, 2014; IEA ETP, 2015).

Technologies	**Investment Cost**	**Fixed Cost**	**Variable Cost**	**Inflexibility (min cap. factor)**	**Capacity Factor^a**	**Efficiency^b**	**Expected lifetime**	**Construction time**
	US$/kW	US$/kW	US$/GJ	% of installed capacity	%	%	Years	Years
Biogas	1905	50	1.8	34	85	40	25	4
Biomass Incineration	1905	13	0.5	34	66	35	25	4
Coal Puverized	2313	44	1	45	85	52	40	4
Coal with CCS	4626	102	1	45	85	44	40	4
Concentrated Solar Power	2160	65	1.7	0	40	35	40	1
Photovoltaics	972	40	0	0	25	25	25	1
Photovoltaics Distributed	1000	40	0	0	32	25	25	1
Fuel Oil	1400	25	1.7	27	85	35	25	2
Geothermal	2508	120	0	0	85	15	20	2
Hydro Large	2939	45	1	13	na	100	60	5
Hydro Small	3499	35	1	13	na	100	60	2
Hydro Strategic Large	2351	26	0	13	na	100	60	5
Natural Gas Combined Cycle	1260	20	2.5	42	85	62	30	3
Natural Gas Open Cycle	583	10	2.5	27	85	42	30	2
Nuclear (PLWR and PHWR)	6318	115	3.1	50	85	37	40	5
Wind off-shore	2592	114	0	0	42	100	25	1
Wind on-shore	1296	36	0	0	31	100	30	1
Distribution lines	1491	0	0	na	na	94-97	60	1
Transmission lines	746	0	0	na	na	95-97	60	1
Transmission Subsystems	448	0	0	na	na	95-97	60	1

[a] Capacity factor for large, small and strategic large hydro varies across the year during wet and dry seasons in each country

[b] For transmission and distribution lines corresponds to technical and non-technical losses depending on the country

Apêndice (Appendix) E – Installed Capacity and Electricity Supply Results

Table E.1
Reference Trade SAMBA Installed Capacity (GW)

Power Plant	South America Neighbours				Brazil			
	2013	**2018**	**2038**	**2058**	**2013**	**2018**	**2038**	**2058**
Nuclear	1.00	1.00	0.00	0.00	2.00	3.40	2.80	0.00
Natural Gas CC	15.05	18.36	10.28	0.25	0.00	0.53	21.11	23.24
Natural Gas OC	18.80	20.51	22.00	17.00	9.96	12.51	4.10	0.00
Fuel Oil	16.76	18.60	4.46	0.78	4.42	5.26	5.37	12.10
Clean Coal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Puverized Coal	7.14	8.94	8.08	41.91	3.16	3.16	10.26	50.03
Biogas	0.00	0.00	0.00	2.46	0.00	0.00	0.00	4.09
Bagasse Incineration	0.69	0.79	12.57	23.43	8.94	10.45	10.87	35.43
Concentrated Solar	0.00	0.00	0.50	29.31	0.00	0.00	0.00	29.78
Photovoltaics	0.10	0.18	0.09	3.40	0.00	0.00	0.00	2.90
Wind On-shore	0.53	1.11	32.31	83.26	1.96	3.74	32.18	53.20
Wind Off-shore	0.00	0.00	0.40	29.72	0.00	0.00	0.00	1.30
Geothermal	0.00	0.25	2.22	11.00	0.00	0.00	0.00	0.00
Small Hydro (< 30 MW)	1.34	1.64	1.74	7.94	5.02	5.65	6.94	7.44
Large Hydro	56.36	72.68	137.18	189.34	80.81	100.88	122.19	131.38
Total Capacity	**117.76**	**144.07**	**231.82**	**439.80**	**116.27**	**145.58**	**215.82**	**350.88**

Table E.2
Integration Trade SAMBA Installed Capacity (GW)

Power Plant	South America Neighbours				Brazil			
	2013	**2018**	**2038**	**2058**	**2013**	**2018**	**2038**	**2058**
Nuclear	1.00	1.00	0.00	0.00	2.00	3.40	2.80	0.00
Natural Gas CC	15.05	18.36	9.47	0.09	0.00	0.53	11.45	11.16
Natural Gas OC	18.80	20.51	21.60	17.36	9.96	12.51	4.10	0.00
Fuel Oil	16.76	18.60	4.35	0.79	4.42	5.26	2.12	9.77
Clean Coal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Puverized Coal	7.14	8.94	9.14	40.67	3.16	3.16	12.59	55.53
Biogas	0.00	0.00	0.00	2.46	0.00	0.00	0.00	2.00
Bagasse Incineration	0.69	0.79	10.53	16.79	8.94	10.45	9.68	29.64
Concentrated Solar	0.00	0.00	0.50	27.76	0.00	0.00	0.00	27.00
Photovoltaics	0.10	0.18	0.09	3.30	0.00	0.00	0.00	0.00
Wind On-shore	0.53	1.11	31.73	82.67	1.96	3.74	26.57	52.70
Wind Off-shore	0.00	0.00	0.40	29.04	0.00	0.00	0.00	0.00
Geothermal	0.00	0.25	1.06	11.00	0.00	0.00	0.00	0.00
Small Hydro (< 30 MW)	1.34	1.64	1.74	7.94	5.02	5.65	6.65	7.34
Large Hydro	56.36	72.68	137.14	190.36	80.81	100.88	120.53	132.56
Strategic Large Hydro	*0.00*	*0.00*	*15.08*	*15.08*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Total Capacity	**117.76**	**144.07**	**242.83**	**445.31**	**116.27**	**145.58**	**196.48**	**327.68**

Table E.3
Alternative Trade SAMBA Installed Capacity (GW)

Power Plant	South America Neighbours				Brazil			
	2013	**2018**	**2038**	**2058**	**2013**	**2018**	**2038**	**2058**
Nuclear	1.00	1.00	0.00	0.00	2.00	3.40	2.80	0.00
Natural Gas CC	15.05	18.36	11.47	2.58	0.00	0.53	28.49	32.37
Natural Gas OC	18.80	20.51	25.14	24.46	10.64	13.19	4.10	0.00
Fuel Oil	16.76	18.60	4.45	2.84	4.42	5.26	5.90	5.41
Clean Coal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Puverized Coal	7.14	8.94	8.12	34.73	2.48	2.48	7.28	39.45
Biogas	0.00	0.00	0.00	39.76	0.00	0.00	0.00	22.27
Bagasse Incineration	0.69	0.79	11.06	17.68	8.94	10.45	10.93	35.39
Concentrated Solar	0.00	0.00	0.80	42.28	0.00	0.00	0.00	28.00
Photovoltaics	0.10	0.18	0.09	3.30	0.00	0.00	0.00	2.00
Distributed Photovoltaics	0.00	0.00	0.00	0.00	0.00	0.00	7.36	23.38
Wind On-shore	0.53	1.11	45.50	100.74	1.96	3.74	34.62	53.40
Wind Off-shore	0.00	0.00	0.40	29.63	0.00	0.00	0.00	0.57
Geothermal	0.00	0.25	4.86	11.00	0.00	0.00	0.00	0.00
Small Hydro (< 30 MW)	1.34	1.64	1.74	7.94	5.02	5.65	6.40	7.59
Large Hydro	56.36	72.68	117.16	166.62	80.81	100.88	106.66	111.26
Total Capacity	**117.76**	**144.07**	**230.80**	**483.54**	**116.27**	**145.58**	**214.53**	**361.07**

Table E.4
Reference Trade SAMBA Electricity Supply (TWh)

Power Plant	South America Neighbours				Brazil			
	2013	2018	2038	2058	2013	2018	2038	2058
Nuclear	5.7	4.4	0.0	0.0	2.8	14.9	15.5	0.0
Natural Gas CC	83.3	92.3	61.3	1.5	0.0	1.9	77.7	85.5
Natural Gas OC	70.8	41.7	47.3	37.2	15.7	24.1	7.5	0.0
Fuel Oil	38.5	41.4	7.8	0.1	8.1	0.0	1.7	2.2
Clean Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Puverized Coal	39.1	47.6	41.6	190.5	10.6	10.0	55.1	197.2
Biogas	0.0	0.0	0.0	7.8	0.0	0.0	0.0	1.9
Bagasse Incineration	2.0	3.7	41.7	50.6	47.7	47.5	63.2	206.7
Concentrated Solar	0.0	0.0	1.8	95.5	0.0	0.0	0.0	102.7
Photovoltaics	0.2	0.3	0.1	6.0	0.0	0.0	0.0	6.0
Wind On-shore	1.4	2.9	87.5	224.4	4.9	12.3	112.7	184.1
Wind Off-shore	0.0	0.0	1.5	108.9	0.0	0.0	0.0	5.6
Geothermal	0.0	1.8	15.5	77.1	0.0	0.0	0.0	0.0
Small Hydro (< 30 MW)	1.2	6.2	7.2	38.2	22.3	19.8	36.0	38.9
Large Hydro	282.6	343.6	665.0	947.4	391.2	479.3	584.2	623.3
Total Production	**524.9**	**586.0**	**978.3**	**1785.1**	**503.3**	**609.7**	**953.4**	**1454.1**
Net Imports	**-40.2**	**-34.9**	**-19.9**	**-6.2**	**40.2**	**34.9**	**19.9**	**6.2**
Total Demand	**405.9**	**467.0**	**850.1**	**1644.8**	**464.5**	**536.7**	**842.4**	**1322.3**

Table E.5
Integration Trade SAMBA Electricity Supply (TWh)

Power Plant	South America Neighbours				Brazil			
	2013	2018	2038	2058	2013	2018	2038	2058
Nuclear	5.7	4.4	0.0	0.0	2.8	14.9	12.3	0.0
Natural Gas CC	83.3	89.2	55.9	0.7	0.0	1.9	42.1	41.0
Natural Gas OC	70.8	41.7	46.4	38.1	15.7	24.1	7.5	0.0
Fuel Oil	38.5	41.4	7.8	0.1	8.1	0.0	0.7	1.7
Clean Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Puverized Coal	39.1	47.6	49.4	180.8	10.6	10.0	55.7	218.9
Biogas	0.0	0.0	0.0	5.6	0.0	0.0	0.0	0.9
Bagasse Incineration	2.2	3.7	39.0	51.0	47.7	47.1	56.3	172.9
Concentrated Solar	0.0	0.0	1.8	92.6	0.0	0.0	0.0	93.3
Photovoltaics	0.2	0.3	0.1	5.8	0.0	0.0	0.0	0.0
Wind On-shore	1.4	2.9	86.0	223.8	4.9	12.3	94.2	183.0
Wind Off-shore	0.0	0.0	1.5	106.5	0.0	0.0	0.0	0.0
Geothermal	0.0	1.8	7.4	77.1	0.0	0.0	0.0	0.0
Small Hydro (< 30 MW)	1.0	6.2	7.3	38.2	22.3	22.0	34.7	38.6
Large Hydro	282.6	343.6	663.6	956.5	391.2	480.7	582.1	632.7
Strategic Large Hydro	*0.0*	*0.0*	*86.5*	*89.0*	*n.a.*	*n.a.*	*n.a.*	*n.a.*
Total Production	**524.9**	**582.9**	**1052.8**	**1865.7**	**503.3**	**613.1**	**885.5**	**1383.0**
Net Imports	**-40.2**	**-31.7**	**-87.6**	**-78.4**	**40.2**	**31.7**	**87.6**	**78.4**
Total Demand	**405.9**	**467.0**	**850.1**	**1644.8**	**464.5**	**536.7**	**842.4**	**1322.3**

Table E.6
Integration Trade SAMBA Electricity Supply (TWh)

Power Plant	South America Neighbours				Brazil			
	2013	2018	2038	2058	2013	2018	2038	2058
Nuclear	5.7	4.4	0.0	0.0	2.8	14.9	17.6	0.0
Natural Gas CC	83.3	92.3	75.6	12.0	0.0	1.9	104.8	119.1
Natural Gas OC	70.8	48.4	59.1	57.9	15.7	24.1	7.5	0.0
Fuel Oil	38.5	41.4	7.8	0.9	8.1	0.0	1.4	0.8
Clean Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Puverized Coal	39.1	47.6	47.4	166.4	10.6	9.8	42.6	182.9
Biogas	0.0	0.0	0.0	4.4	0.0	0.0	0.0	13.4
Bagasse Incineration	2.2	3.7	122.2	174.2	47.7	59.5	63.8	206.4
Concentrated Solar	0.0	0.0	2.8	137.2	0.0	0.0	0.0	96.8
Photovoltaics	0.2	0.3	0.1	5.8	0.0	0.0	0.0	4.4
Distributed Photovoltaics	0.0	0.0	0.0	0.0	0.0	0.0	9.8	31.1
Wind On-shore	1.4	2.9	123.3	273.1	4.9	12.3	120.9	184.6
Wind Off-shore	0.0	0.0	1.5	108.7	0.0	0.0	0.0	2.5
Geothermal	0.0	1.8	34.0	77.1	0	0	0	0
Small Hydro (< 30 MW)	1.0	6.2	7.4	38.4	22.3	11.5	33.6	39.9
Large Hydro	282.6	343.6	583.8	849.0	391.2	475.7	544.2	565.4
Total Production	**524.9**	**592.6**	**1065.2**	**1904.9**	**503.3**	**609.7**	**946.3**	**1447.2**
Net Imports	**-40.2**	**-34.8**	**-21.0**	**-3.6**	**40.2**	**34.8**	**21.0**	**3.6**
Total Demand	**405.9**	**467.0**	**848.4**	**1640.3**	**464.5**	**536.7**	**832.8**	**1291.6**

Apêndice (Appendix) F – Installed Capacity Expansion in Bolivia OSeMOSYS SAMBA Scenarios

Table F.1
Installed Capacity Expansion in Bolivia in 2025

Power Plant	Bolivia - Installed Capacity (GW)									
			2025							
	2013		Scenario I		Scenario II		Scenario III		Scenario IV	
Nuclear	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
Natural Gas CC	0.20	12%	0.20	3%	0.20	3%	0.20	3%	0.20	3%
Natural Gas OC	0.90	55%	2.15	28%	1.91	30%	1.65	25%	1.45	24%
Fuel Oil	0.05	3%	0.05	1%	0.05	1%	0.05	1%	0.05	1%
Clean Coal	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
Puverized Coal	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
Biogas	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
Bagasse Incineration	0.02	1%	0.08	1%	0.08	1%	0.08	1%	0.08	1%
Concentrated Solar	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
Photovoltaics	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
Wind On-shore	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
Geothermal	0.00	0%	0.10	1%	0.10	2%	0.10	2%	0.10	2%
Small Hydro (< 30 MW)	0.14	8%	0.14	2%	0.14	2%	0.14	2%	0.14	2%
Large Hydro	0.34	21%	1.19	15%	1.19	19%	1.19	18%	1.19	20%
Strategic Large Hydro	0.00	0%	3.87	50%	2.67	42%	3.22	49%	2.88	47%
Total Capacity	**1.65**	**100%**	**7.78**	**100%**	**6.34**	**100%**	**6.63**	**100%**	**6.09**	**100%**

Table F.2
Installed Capacity Expansion in Bolivia in 2025

Power Plant	Bolivia - Installed Capacity (GW)									
			2058							
	2013		Scenario I		Scenario II		Scenario III		Scenario IV	
Nuclear	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
Natural Gas CC	0.20	12%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
Natural Gas OC	0.90	55%	0.94	3%	0.68	2%	0.98	3%	1.08	3%
Fuel Oil	0.05	3%	0.00	0%	0.02	0%	0.00	0%	0.23	1%
Clean Coal	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
Puverized Coal	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
Biogas	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
Bagasse Incineration	0.02	1%	0.00	0%	0.00	0%	0.00	0%	0.09	0%
Concentrated Solar	0.00	0%	9.50	27%	9.05	26%	9.10	26%	9.45	27%
Photovoltaics	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
Wind On-shore	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
Geothermal	0.00	0%	0.96	3%	1.24	4%	0.92	3%	0.83	2%
Small Hydro (< 30 MW)	0.14	8%	0.14	0%	0.14	0%	0.14	0%	0.14	0%
Large Hydro	0.34	21%	20.11	57%	21.22	61%	20.39	59%	20.89	59%
Strategic Large Hydro	0.00	0%	3.87	11%	2.67	8%	3.22	9%	2.88	8%
Total Capacity	**1.65**	**100%**	**35.52**	**100%**	**35.02**	**100%**	**34.75**	**100%**	**35.59**	**100%**

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