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FACULDADE DE ENGENHARIA

CAIO MÜLLER

Survey sobre o uso da Dinâmica de Sistemas no Desenvolvimento Energético Sustentável

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CAIO MÜLLER

Survey sobre o uso da Dinâmica de Sistemas no Desenvolvimento Energético Sustentável

Monografia submetida à Faculdade de Engenharia da Universidade Federal de Juiz de Fora como parte dos requisitos para obtenção do grau de Bacharel em Engenharia Elétrica.

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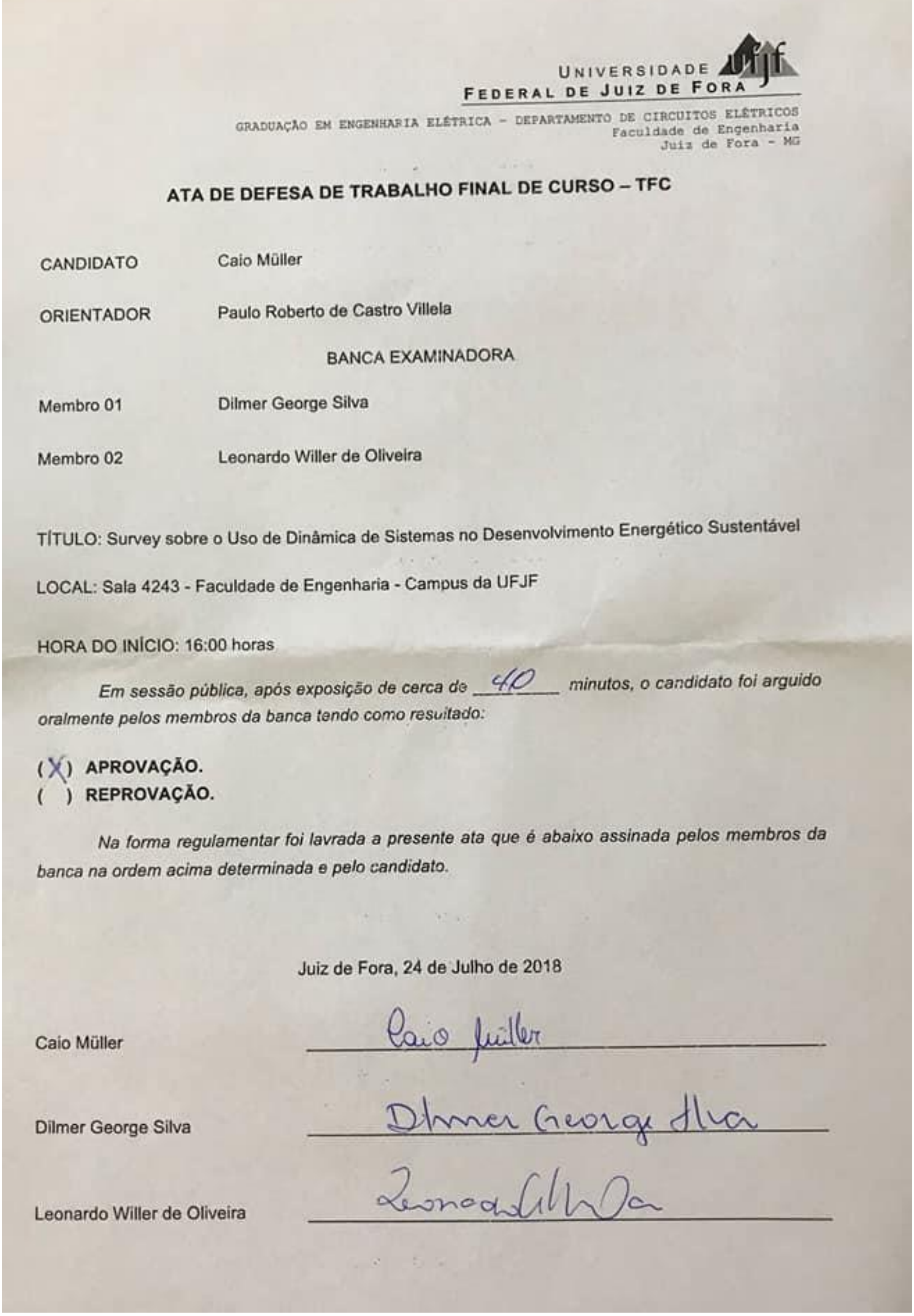

UNIVERSIDADE
FEDERAL DE JUIZ DE FORA

GRADUAÇÃO EM ENGENHARIA ELÉTRICA - DEPARTAMENTO DE CIRCUITOS ELÉTRICOS
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ATA DE DEFESA DE TRABALHO FINAL DE CURSO – TFC

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TÍTULO: Survey sobre o Uso de Dinâmica de Sistemas no Desenvolvimento Energético Sustentável

LOCAL: Sala 4243 - Faculdade de Engenharia - Campus da UFJF

HORA DO INÍCIO: 16:00 horas

Em sessão pública, após exposição de cerca de 40 *minutos, o candidato foi arguido oralmente pelos membros da banca tendo como resultado:*

☒ **APROVAÇÃO.**
☐ **REPROVAÇÃO.**

Na forma regulamentar foi lavrada a presente ata que é abaixo assinada pelos membros da banca na ordem acima determinada e pelo candidato.

Juiz de Fora, 24 de Julho de 2018

Caio Müller Caio Müller

Dilmer George Silva Dilmer George Silva

Leonardo Willer de Oliveira

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RESUMO

Nos últimos anos, tem-se estudado bastante sobre o desenvolvimento energético sustentável, emissão de dióxido de carbono, fontes alternativas de energia e mudança climática. Vários pesquisadores publicaram artigos sobre esse tema com uma abordagem utilizando-se dinâmica de sistemas. Esta monografia apresenta um survey dos trabalhos cujas palavras-chave possuíam principalmente dióxido de carbono, fontes energéticas, energias renováveis, mudanças climáticas, combustíveis fósseis e obrigatoriamente dinâmica de sistemas.

PALAVRAS CHAVE: 1. Desenvolvimento Energético Sustentável; 2. Dinâmica de Sistemas; 3. Survey; 4. Dióxodo de Carbono; 5. Fontes Energéticas

ABSTRACT

In recent years, there has been a lot of research on sustainable energy development, carbon dioxide emissions, alternative energy sources and climate change. Several researchers have published articles on this topic using a systems dynamics approach. This monograph presents a survey of the works whose keywords had mainly carbon dioxide, energy sources, renewable energies, climate change, fossil fuels and compulsory systems dynamics.

Keywords: 1. Sustainable Energy Development; 2. System Dinamics; 3. Survey; 4. Carbon Dioxide; 5. Energy Sources

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CAPÍTULO 1

INTRODUÇÃO

Dinâmica de Sistemas é uma técnica de simulação computacional desenvolvida pelo engenheiro eletricista Jay Forrester (1918 - 2016) do Massachusetts Institute of Technology, que tem sido usada para analisar sistemas em diversas áreas do conhecimento, em particular sistemas de energia em geral, como será mostrado ao longo deste trabalho.

Espera-se que esta monografia traga como contribuição chamar a atenção e despertar o interesse no desenvolvimento de projetos futuros, nessa linha aqui apresentada, pelos alunos do curso de Engenharia Elétrica.

O que se vai mostrar aqui é um vasto material, com um grande potencial de uso em linhas de pesquisas relacionadas com a tomada de decisão, operação e planejamento dinâmico de sistemas energéticos, considerando múltiplos aspectos, isto é, não somente aqueles de natureza energética ou elétrica, em particular.

1.1 Objetivo

O objetivo desta monografia é mostrar como a técnica de simulação computacional conhecida como Dinâmica de Sistemas, criada por Jay Forrester no final da década de 1950 (FORRESTER, 1961), tem sido usada por pesquisadores do mundo todo na abordagem da complexidade da tomada de decisões, operação e planejamento na área energética.

1.2 Estrutura do Trabalho

Este documento está estruturado em 5 capítulos e 2 apêndices. Neste Capítulo 1 é feita esta introdução.

No Capítulo 2, são apresentados os conceitos relacionados com Dinâmica de Sistemas e Desenvolvimento Energético Sustentável.

No Capítulo 3 são analisados em detalhe dois importantes artigos (AHMAD et al., 2016; TEUFEL et al., 2013) que abordam o uso de Dinâmica de Sistemas no setor elétrico.

No Capítulo 4 é feito um survey sobre o uso de Dinâmica de Sistemas no desenvolvimento energético sustentável.

E, no Capítulo 5, são apresentadas a conclusão e propostas de trabalhos futuros.

No Apêndice A é fornecido o artigo original "Review of System Dynamics models for electricity market simulations" de Teufel et al., publicado em 2013.

No Apêndice B é anexado o artigo original "Application of system dynamics approach in electricity sector modelling: A review" de Ahmad et al., publicado em 2016.

1.3 Metodologia

Metodologicamente foram buscados artigos e livros em periódicos e universidades. tendo-se chegado à catalogação de 74 publicações. Duas destas, publicadas na forma de *surveys*, foram de capital importância para nosso estudo pois, além de constituirem excelentes fontes de pesquisa e de metodologia, mostraram as lacunas a serem preenchidas neste documento.

Levando-se em conta que uma das principais preocupações do mundo atual é o desenvolvimento sustentável, não somente econômico, mas também social e ambiental, foca-se no Capítulo 4, em elaborar um *survey* a partir de uma busca na literatura de artigos sobre desenvolvimento de sistemas energéticos sustentáveis e que usam como técnica de análise a Dinâmica de Sistemas.

CAPÍTULO 2

CONCEITOS

2.1 Dinâmica de Sistemas

A dinâmica de sistemas é uma ferramenta que permite ao usuário identificar entre as variáveis do problema, relações de causa e efeito, o tempo de resposta das variáveis e se há efeito de realimentação. (VILLELA, 2006)

As relações de causa e efeito desempenham o papel de mostrar ao usuário o comportamento de um par de variáveis, qual o impacto em uma variável se há crescimento ou redução de outra variável. O tempo de resposta representa quão rápido uma variável pode interferir na outra. Com o tempo de resposta é possível entender se a reação será imediata ou ocorrerá um atraso. A realimentação do sistema tem o intuito de estabilizar em um ponto. (VILLELA, 2006)

2.1.1 Histórico

Em meados do século passado, o engenheiro Jay Forrester propôs uma técnica que envolvesse engenharia e gestão educacional. Utiliza-se principalmente de efeitos de realimentação, a decisão tomada em uma determinada etapa influenciaria o meio na qual essa se encontra. Com esta análise, as estruturas de circuito aberto poderiam não ser fiéis se comparadas com a malha fechada. (FORRESTER, 1968)

A publicação do livro “Industrial Dynamics” (FORRESTER, 1961) marcou o fim do primeiro período da dinâmica de sistemas. Neste período, muitos exemplos para estado estacionário foram desenvolvidos. O maior foco desses projetos era a engenharia empresarial. (FORRESTER, 1968)

O segundo período foi marcado pela atuação nas áreas de ciências sociais. O desenvolvimento dessa técnica avançou e tornou-a generalizada para as diversas áreas de conhecimento. Com essa generalização, era possível elaborar um modelo que englobasse engenharia, gestão, medicina, economia e psicologia e explicitar como uma área interferiria na outra. (FORRESTER, 1968)

O terceiro período é marcado pela publicação do livro “World Dynamics” (FORRESTER, 1971). Nesta obra, Forrester apresenta modelos de crescimento populacional e utilização de recursos naturais que, sem interferências políticas, poderiam resultar em crises de fome e poluição. (FORRESTER, 1969; SANNINO, 2006)

2.1.2 Diagrama Causal

Segundo Villela (2006) “Os modelos causais são diagramas que servem para descrever uma situação-problema de acordo com o que pensa cada observador. São modelos que procuram explicitar as relações de causa e efeito dentro do contexto do problema.”

A simbologia para se desenhar diagramas causais é apresentada na figura 1. A seta indica que alterações na Variável A causam alterações na Variável B. O símbolo **positivo (+)** indica que um aumento (diminuição) na Variável A causa uma variação no **mesmo sentido** na Variável B, isto é, aumento (diminuição). O símbolo **negativo (-)** indica que um aumento (diminuição) na Variável A causa uma variação no **sentido oposto** na Variável B, isto é, diminuição (aumento). Os dois traços verticais (||) colocados sobre a seta, similar a um capacitor, indica que as alterações na Variável B ocorrem **um certo tempo depois** das alterações na Variável A. (VILLELA, 2006)

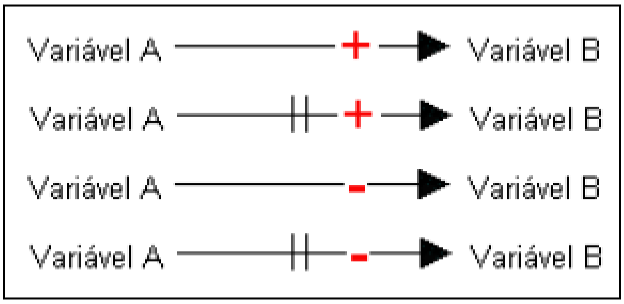

Figura 1 – Simbologia de um Diagrama Causal
Fonte: (VILLELA, 2006)

A figura 2 exemplica como se deve ler a relação causal entre duas variáveis de um sistema. A "quantidade de remédio tomada" influencia positivamente a "quantidade de remédio acumulada no organismo", isto é, se a ingestão de uma quantidade maior de remédio, acarretará um acréscimo na quantidade de remédio acumulada no organismo.

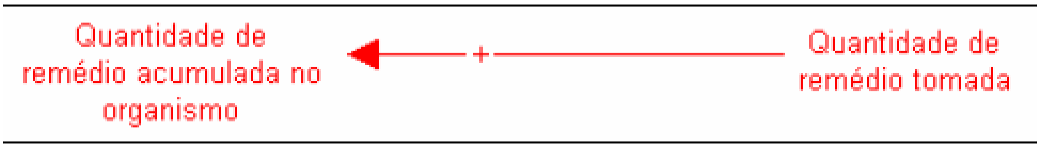

Figura 2: Exemplificação de Relação Causal entre Duas Variáveis
Fonte: (VILLELA, 2006)

A figura 3 exemplica o modelo causal de como se dá a capitalização de uma caderneta de poupança bancária. Quanto maior a "Taxa de Rendimento Mensal" (juros) maior o "Rendimento Mensal". E quanto maior este, maior a "Poupança Acumulada". E quanto maior esta, maior o "Rendimento Mensal". Existe uma realimentação positiva no sistema pois quanto maior a "Poupança Acumulada", maior o "Rendimento Mensal", maior a "Poupança Acumulada" e assim por diante.

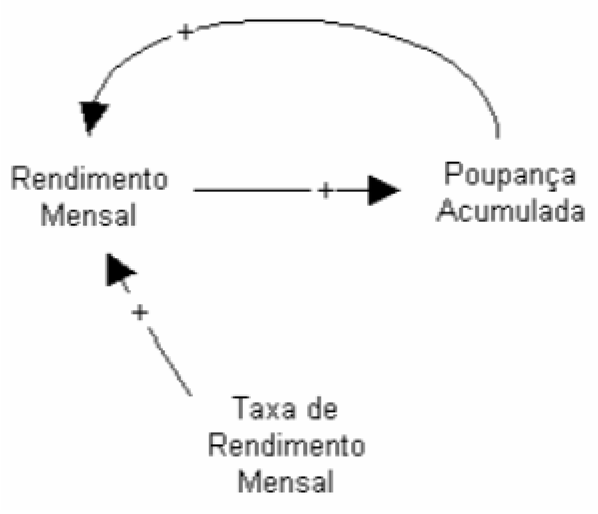

Figura 3: Modelo Causal de uma Aplicação Financeira numa Caderneta de Poupança
Fonte: (VILLELA, 2006)

2.1.3 Diagrama de Estoque e Fluxo

Os diagramas causais são qualitativos. Para se trabalhar com relações quantitativas são usados os diagramas de estoque e fluxo em Dinâmica de Sistemas.

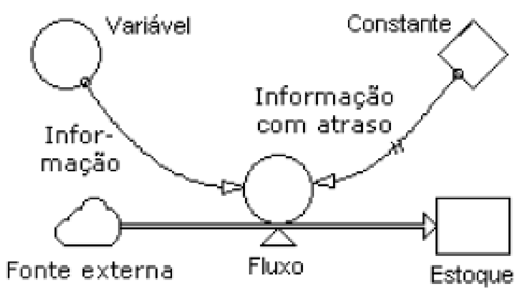

Figura 4: Diagrama de Estoque e Fluxo
Fonte: (VILLELA, 2006)

A figura 4 exemplifica um diagrama de estoque e fluxo simples com seus principais elementos. **Variáveis** são representadas por **círculos** e **constantes** por **losangos**. **Estoques** são variáveis cumulativas e são representados por **retângulos**. A **nuvem** representa **fonte externa** ao contexto do sistema. **Fluxo** representa o **movimento** de alguma grandeza que **entra ou sai de um estoque**. Fluxos são representados por uma **seta com traço duplo**. **Normalmente** um **fluxo é controlado** por uma variável (círculo) com um triângulo abaixo dela, fazendo lembrar uma "torneira que controla o fluxo de água num cano. As **setas com traço simples** representam **informações** que ligam variáveis. Se há um **traço duplo** (semelhante a um capacitor) na seta de informação, significa que há um **atraso na propagação** dessa informação.

2.2 Desenvolvimento Energético Sustentável

2.2.1 Introdução

A palavra sustentabilidade tem origem na palavra em latim “sustentare”. Em 1987, A Organização das Nações Unidas, em um relatório sobre meio ambiente e desenvolvimento, introduz o conceito de desenvolvimento sustentável como “O desenvolvimento que satisfaz as necessidades presentes, sem comprometer a capacidade das gerações futuras de suprir suas próprias necessidades”. (ONU, 1987)

2.2.2 Pilares de Sustentabilidade

Ainda de acordo com a Organização das Nações Unidas, para que algo seja sustentável, ele precisa se enquadrar em 3 indicadores, também conhecidos como os pilares da sustentabilidade. Portanto, é sustentável quando se possui os pilares social, econômico e ambiental e eles interagem de forma harmoniosa entre si. (ONU, 2005)

A figura 5 explica a correlação entre essas variáveis.

Figura 5 – Pilares da Sustentabilidade
Fonte: (RODRIGO, 2011)

2.2.3 Sustentabilidade Energética

A sustentabilidade energética é quando a sustentabilidade possui como fim a energia, ou seja, suprir a demanda energética atual sem comprometer a geração futura de conseguir recursos para suprir sua demanda. Então, introduz-se dois novos conceitos de pilares para a sustentabilidade energética: a eficiência energética e fontes renováveis. (FAPESP, 2007)

2.2.3.1 Eficiência Energética

Eficiência energética é um conceito utilizado para realizar um mesmo trabalho com o uso inteligente da energia disponível. Assim, um determinado trabalho consegue ser realizado de forma convencional e de forma eficiente. Este último é um desafio que a Engenharia está enfrentando nos últimos tempos e continuará sendo, na medida em que a tecnologia avança. (ELEKTRO, 2012)

2.2.3.2 Fontes Renováveis de Energia

As fontes renováveis de energia, segundo a literatura, são aquelas que são obtidas por fluxos repetitivos e imediatos no meio ambiente. Já as fontes não renováveis são fnitas, encontradas em estoque estático e cuja capacidade de regeneração possui um intervalo de tempo longo. (TWIDELL, 2006)

Alguns exemplos de fontes não renováveis são: carvão, gás, petróleo; já para fontes renováveis são conhecidas: solar, hidráulica, eólica.

CAPÍTULO 3

DINÂMICA DE SISTEMAS APLICADA AO SETOR ELÉTRICO

Neste capítulo são analisados dois importantes artigos que abordam o uso de dinâmica de sistemas na análise do setor elétrico. Também são classificadas as categorias voltadas para o meio ambiente.

3.1 Análise do artigo "Application of system dynamics approach in electricity sector modelling: A review"

Ahmad et al. (2016) em “Application of system dynamics approach in electricity sector modelling: A review”, faz uma revisão dos artigos do período de 2000 até 2013 relacionados ao setor elétrico de energia e dinâmica de sistemas. Os autores classificam os artigos em:

- Modelos de Avaliação de Políticas;
- Modelos de Expansão da Capacidade de Geração;
- Modelos de Instrumentos Financeiros;
- Modelos de Métodos Mistos;
- Modelos de Gerenciamento de Demanda;
- Modelos Micro-Mundos.

Na introdução é citado que os autores “Jebaraj e Iniyan (2006) revisaram modelos de energia visados para o planejamento da expansão e demanda de energia; previsão e otimização; rede neural e modelo fuzzy. Os autores Bazmi e Zahedi (2011), Baños et al. (2011), e Foley et al. (2010) também fizeram uma revisão em otimização de planejamento de energia. Connolly et al. (2010) revisaram simulação computacional para otimização em energias renováveis.”

O modelo de avaliação política é composto por “ política para investidores privados; políticas para a desregulamentação do mercado de energia; comércio internacional de eletricidade; políticas de incentivo às renováveis para a substituição dos combustíveis fósseis; e economia ambiental.”

A primeira análise desse artigo é feita sobre o modelo de Qudrat-Ullah e Davidsen (2001). Este artigo relata sobre a produção de energia pelo produto doméstico bruto e sua geração de gases de efeito estufa. Ahmad et al. (2016) não concordam com Qudrat-Ullah e Davidsen (2001) dizendo que apenas o produto doméstico bruto possa ser suficiente para agravar o problema na camada de ozônio na atmosfera, “outros fatores macroeconômicos, como imposto de eletricidade possa ser mais apropriado para o modelo de um país em desenvolvimento.” E foi com essa ideia que Qudrat-Ullah e Karakul (2007) escreveram um artigo onde, eles acreditavam que os incentivos governamentais não eram suficientes para cobrir a demanda futura ao longo prazo. “Tirando a hidroeletricidade, nenhuma outra forma de energia renovável foi avaliada para o estudo.”

O modelo de Kilanc e Or (2006) foi classificado na desregulamentação da indústria elétrica. Ao contrário dos artigos mencionados anteriormente, este leva em consideração a inserção de energia na rede. “A imperfeição deste modelo se dá na previsão de decisão dos investidores e nos atrasos de construção de usinas geradoras de energia resultando em flutuação do preço da energia elétrica. Outro fator importante de se considerar é que não se encontrava no modelo nenhum tipo de mecanismo para intervir no poder de mercado dos investidores.” Ochoa (2007) relatava em seu trabalho que na Suécia, é preciso retirar de operação algumas usinas nucleares e resolver o problema do abastecimento de energia sem afetar significativamente o preço de energia elétrica. “O modelo de Ochoa (2007) não levava em conta as restrições ambientais nem as linhas de transmissão de energia elétrica” resultando que a solução era de se importar energia para a Suécia. Ochoa e van Ackere (2009), Ochoa aperfeiçoou seu modelo provando que era essencial para o país importar energia internacional. Outra solução rápida era de se instalarem usinas térmicas na Suécia, assim seria resolvido o problema de energia segura, em contrapartida, acarretaria em mais emissão de gás carbônico na atmosfera.

Outra citação, é de Cimren et al. (2010) com base no modelo de Ochoa e van Ackere, que desenvolveu um modelo para análise de queima de lixo para eletricidade em Ohio nos Estados Unidos. Ahmad et al. (2016) perceberam que esta pesquisa, ao contrário das outras, defendia que o problema principal era político e não econômico, “pois esse além de reduzir os gases de efeito estufa, também gera empregos.”

Ahmad et al. também faz uma análise do modelo de Zhao et al. (2011) que avalia o crédito de investimento de imposto (investment tax credit) e a tarifa de alimentação (Feed-in Tariff) para o sistema fotovoltaico residencial. “Ao contrário de Qudrat-Ullah e Davidsen (2001), a variável de crescimento de demanda não foi explicitada.” O objetivo do trabalho era de se calcular o payback do investimento da pessoa física ao se instalar essa tecnologia em sua residência. “As simulações demonstram que a política de incentivo acelerou o processo de adoção dessa tecnologia.”

Um trabalho estudado com foco em água e eletricidade na Austrália foi o de Newell et al. (2011). Diferente dos seus predecessores, seu diagrama causal leva em conta a segurança de alimentos vinculada à produção de eletricidade por hidrogeração, não apenas o dióxido de carbono. Assim como Kilanc e Or (2006), há algumas imperfeições no modelo como por exemplo “mudar facilmente o mercado australiano e aumentar o diálogo setorial para lidar com questões de eletricidade e água de forma abrangente, além de faltar coerência no diagrama causal e não levar em conta as energias renováveis para geração de energia.”

O modelo mexicano batizado de REFELECTe pelos autor Fuentes-Bracamontes (2012) também é estudado. A diferença deste trabalho para os outros foi a lógica se-então (IF-THEN-ELSE), para as escolhas das tecnologias adotadas. O autor fornece as equações utilizadas para o modelo, mas não mostra seu diagrama causal. “A saída do modelo revelou que a competição nas tecnologias de combustíveis fósseis, mantendo o controle da capacidade hídrica e nuclear com o governo, atingiu a meta de segurança ambiental e de suprimento, além de manter o preço dentro da faixa aceitável.” Seguindo Fuentes-Bracamontes (2012), o trabalho de Saysel e Hekimoglu (2013) discute diminuir as emissões de dióxido de carbono utilizando energias renováveis. “O estudo consegue implementar essa política de energias renováveis, mas peca em não abordar fatores externos dessa tecnologia.”

Os artigos com foco na expansão da capacidade de geração de energia elétrica (generation capacity expansion) pecam em vários aspectos. “Alguns estudavam várias formas de energias, enquanto outras estudavam só uma além de considerar as condições perfeitas para o mercado e tecnologias maduras.”

De acordo com Ahmad et al. (2016), “as decisões da geração de energia elétrica foram tomadas com base na avaliação da lucratividade de um determinado investimento. Houve um atraso entre a decisão de investimento sendo tomada e a capacidade real de geração entrar em operação. A lacuna oferta-demanda, juntamente com o custo de capital da tecnologia e o preço de mercado da eletricidade, foram os fatores cruciais a serem considerados para o retorno do investimento.” Há uma lacuna entre a geração e o pico de carga e para diminuir esta lacuna, o governo fornece incentivo para os empresários para extinguir esta diferença. E quanto maior for esta diferença, maiores serão os incentivos.

A figura 6, retirada do artigo original, mostra visualmente as relações descritas no parágrafo anterior através de um modelo causal genérico. Nota-se que o autor fornece o sentido das relações entre as variáveis, mas não a relação de como estas interferem uma nas outras.

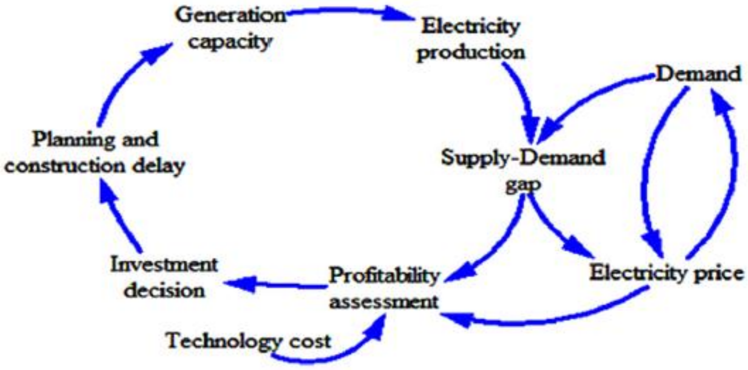

Figura 6: Modelo Causal Genérico de Expansão de Geração
Fonte: (AHMAD ET AL., 2016)

Gary e Larsen (2000) desconsideraram o decomissionamento de usinas para seu modelo, o que pode gerar erros na simulação, mas consideraram a vida útil e eficiência dos equipamentos. O modelo de Ford (2001) utiliza um preço médio para a eletricidade, enquanto Olsina et al. (2006) utilizam o preço baseado na curva de demanda e geração de carga. A única suposição que faltou foi implementada no modelo de Hasani- Marzooni e Hosseini (2011) que é considerar o preço da eletricidade como sendo elástico, como por exemplo ao se adotar medidas de eficiência energética para frear o crescimento da curva de carga. “O resultado de todos os modelos, independente da diferença geográfica, demonstraram um mesmo comportamento cíclico na capacidade operacional total e no preço da eletricidade.”

Para o caso da lacuna mencionada anteriormente, Park et al. (2007) desenvolveram um artifício para calcular o valor desse investimento baseado no cálculo de probabilidade de perda usando decaimento exponencial. As análises dos resultados foram que “o valor de investimento para suprir o valor de pico é muito maior comparado para suprir a carga base.” Assili et al. (2008) diferente de Park et al. (2007), usou função de distribuição binomial para seu modelo e Hasani e Hosseini (2011) fizeram por um mecanismo híbrido ou variável fixa.

Ahmad et al. (2016) conclui dizendo que “os modelos de expansão da capacidade de geração com mecanismo de pagamento de capacidade mostraram que os ciclos ou oscilações observadas no problema dessa expansão foram reduzidos, independentemente do tipo de mecanismo de pagamento de capacidade empregado. Além disso, parecia que os pagamentos de capacidade variável eram melhores que os mecanismos de pagamento fixo. Modelos revisados nesta categoria explicaram que era difícil equilibrar oferta e demanda no setor elétrico. Foi encontrado que o investidor precisava de um apoio financeiro contínuo para garantir margem de segurança de capacidade. No momento, parecia que as tecnologias de combustíveis fósseis eram as preferidas em relação às tecnologias renováveis nos modelos de expansão.”

Os modelos de instrumentos financeiros segundo Ahmad et al. (2016) “são mecanismos de incentivo às energias renováveis como o certifica de zero emissão (Zero-Emission Certificate), certificado verde comercializável (Tradable Green Certificates), as tarifas de alimentação e um modelo geral desenvolvido por Alishahi et al. (2012).”

O certificado verde comercializável de Ford et al. (2007) e o certificado de zero emissão de Kunsch et al. (2004) acreditavam em uma estrutura genérica de geração e de demanda para estes certificados, que poderiam ser vendidos no mercado e com isso, aumentar a receita dessas empresas de energias renováveis. Em ambos os artigos, há uma redução nas emissões dos gases de efeito estufa. No trabalho de Kunsch et al. (2004) é levada em consideração o decomissionamento de usinas, já no de Ford et al. (2007) não. “Um pequeno deslize de Kunsch et al. (2004) foi manter essas políticas no cenário incerto de longo-prazo.”

Assim como Ford at al. (2007), Hasani-Marzooni e Hosseini (2012) trabalharam com um modelo de certificado verde de troca para energia eólica. O que difere estes autores de Ford et al. (2007), foram as modelagens das variáveis desse certificado e de preço de energia elétrica, além de se considerar o fator de capacidade variada. Outra diferença foram os objetivos de cada artigo. Enquanto Ford et al. (2007) miram suprir a demanda, Hasani-Marzooni e Hosseini (2012) testam a viabilidade do projeto. Ahmad et al. (2016) perceberam que em ambos os projetos o valor do certificado anterior é alto para quando há uma diferença de capacidade eólica prevista para uma capacidade eólica construída. “E quando esta diferença é zerada, o valor do certificado despenca.” Nesta área de atuação Alishahi et al. (2012) avaliaram vários tipos de incentivos para elevar este fator de capacidade. Em contraste com os outros dois autores mencionados, Alishahi et al. (2012) usam um método probabilístico de viabilidade das correntes de vento. O modelo é dividido em duas simulações, nas quais, uma é fixa e outra é dependente do mercado de eletricidade. “Os resultados mostram que o fator fixo atinge um valor de capacidade maior do que o dependente do mercado.”

Ainda neste tema, em Taiwan, Hsu (2012) desenvolve um modelo para estudar as tarifas de alimentação sobre os painéis fotovoltaicos. As simulações indicam que ao se aumentar as taxas de tarifas, os investimentos de painéis fotovoltaicos aumentam.

Ahmad et al. (2016) concluem esta classificação dizendo que os diagramas de dinâmica de sistemas estudados não levam em conta a parte social, estão voltadas para a parte econômica e ambiental apenas, dois dos três pilares da sustentabilidade.

A classe de modelos de métodos mixos não foca em resultados, nem em estrutura do problema, apenas em relatar os métodos utilizados juntos com dinâmica de sistemas.

O modelo de Dimitrovski et al. (2007) usam otimização implementada no software MATLAB para o preço de eletricidade horária junto com o modelo de dinâmica de sistemas construída no software VENSIM. Pereira e Saraiva (2011) também utilizaram o MATLAB e otimização, mas com algoritmos genéticos. O modelo de dinâmica de sistemas foi implementado no software PSIM. Para fazer o elo entre os dois programas, foi utilizada o ambiente Microsoft EXCEL. Tan et al. (2010) abordaram um sistema de escolha de ramos de árvores, todavia, nenhum software foi mencionado no estudo.

A próxima categoria estudada por Ahmad et al. (2016) diz respeito ao uso mais eficiente da energia, seja substituindo tecnologias antigas por novas ou alterando o tempo de uso de energia.

O artigo de Dyner e Franco (2004) estuda a substituição de lâmpadas incandescentes por fluorescentes. Seus resultados mostram que quanto maior o número de lâmpadas fluorescentes nas residências, menor o número de lâmpadas incandescentes. Ben Maalla e Kunsch (2008) pesquisam sobre a adoção da tecnologia doméstica de energia térmica. Como previsto, o efeito de se adotar nova tecnologia é mostrado em uma curva cuko formato se assemelha a letra S.

Elias (2008) desenvolveu um esquema para identificar a crescente demanda de eletricidade residencial na Nova Zelândia. Seus resultados foram de que o comportamento das pessoas é a forma mais eficiente de se reduzir a demanda.

Apenas dois artigos relatam sobre os micro-mundos para o setor elétrico. Dyner et al. (2009) criaram o EnerBiz na Colômbia e Paşaoğlu (2011) criou o Liberalised Electricity Market Micro-world na Turquia. Ambos foram testados em seus respectivos países e seus resultados foram idênticos. “Os dois micro-mundos focam em geração, ajudando na tomada de decisões, mas pecam em novas tecnologias, como as renováveis por exemplo.”

A conclusão de Ahmad et al. (2016) foi de que “neste trabalho, um esforço foi feito para destacar a contribuição da modelagem da dinâmica de sistemas do setor elétrico. A análise revelou que a avaliação de políticas e a expansão da capacidade de geração foram as duas questões mais modeladas. Modelos de avaliação de políticas foram desenvolvidos em nível nacional para obter informações sobre o efeito de novas políticas. Essas políticas incluem o incentivo a investimentos do setor privado, a eliminação nuclear ou a desregulamentação do setor. A expansão da capacidade de geração abordou a confiabilidade e a capacidade financeira do sistema de geração. Simulações destacaram a dependência e interação de decisões de investimento em cálculos de rentabilidade. Verificou-se um pagamento por capacidade de mercado para garantir o cronograma das expansões de geração, mas esse mecanismo não conseguiu eliminar os ciclos de investimento. Modelos na categoria de instrumentos financeiros estavam preocupados em impulsionar as tecnologias renováveis para geração de eletricidade em um mercado competitivo. Na categoria de métodos mistos, a flexibilidade da dinâmica de sistemas com outras ferramentas e técnicas foi confirmada. Na categoria de gerenciamento de demanda, constatou-se que a divulgação de informações sobre o uso racional de energia é crucial para influenciar a demanda. Finalmente, na categoria micro-mundos, a importância de aprender e experimentar nos mercados de eletricidade foi afirmada. Devido ao valor comercial, não há muitos artigos relatados em micro-mundos. Além disso, a revisão revelou que existe uma estrutura genérica de oferta e demanda sob todos os modelos. As mudanças nas condições e regulamentações do mercado, que perturbam o equilíbrio entre oferta e demanda, foram o principal motivo para o uso da abordagem de dinâmica de sistemas.”

3.2 Análise do artigo "Review of System Dynamics models for electricity market simulations”

Neste artigo de Teufel et al. (2013), é estudado dinâmica de sistemas aplicada ao mercado de eletricidade. Após introduzir o tema, os autores fazem uma classificação dos modelos do mercado de eletricidade que são do tipo:

- Top-Down
    - Input-Output
    - Computable General Equilibrium
- Bottom-Up
    - Optimization
    - Simulation

A classificação de Bottom-Up foca nos modelos de otimização e de simulação de determinados setores. Já os de Top-Down, tem um enfoque em modelos de equilíbrio com ênfase na perspectiva macroeconômica.

O segundo assunto debatido são as particularidades da modelagem de mercado de eletricidade. Nesta parte é dada uma revisão histórica de dinâmica de sistemas.

Após explicar como surgiu a dinâmica de sistemas no modelo de mercado de eletricidade, uma nova classificação é feita e se divide em:

- Mercados Regulares de Eletricidade
    - Política de Recurso
    - Ciclos de Investimento e Decisões de Investimento
- Mercados Liberais de Eletricidade
    - Capacidade de Geração
    - Design de Mercado
    - Rede de Transmissão e Acoplamento de Mercado
    - Modelos Extensivos de Mercado
    - Aplicação Pedagógica e Jogos de Guerra de Negócios

A primeira classificação, a política de recurso dos mercados regulares de eletricidade apresenta o modelo World3 de Meadows et al. (1972) e a partir deste modelo, Naill (1972) aprimora esse modelo e cria o COAL1 e COAL2 para avaliar as políticas energéticas dos Estados Unidos no longo prazo. FOSSIL1 e FOSSIL2 foram os primeiros modelos desenvolvidos voltados para o setor elétrico. A partir do FOSSIL2, vieram outros modelos como o "Integrated Dynamic Energy Analysis Simulation" e "Feedback Rich Energy Economy". O primeiro modelo é um software de simulação que analisa a dependência de petróleo dos Estados Unidos. O de Fiddaman (1997) relaciona os pilares da sustentabilidade, com foco em desenvolvimento de energia e demanda de energia. A figura 7 feita por Teufel et al. (2013) apresenta uma linha do tempo com os trabalhos mencionados.

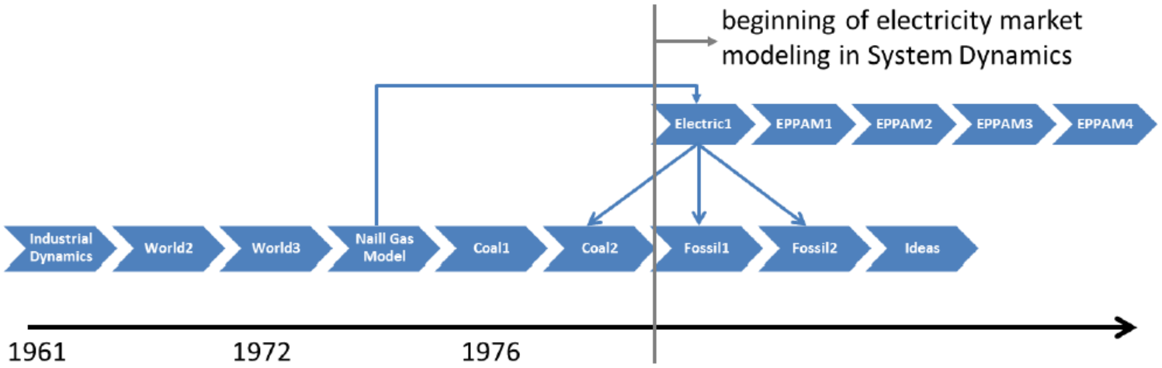

Figura 7: Linha do Tempo dos Trabalhos
Fonte: (TEUFEL ET AL., 2013)

Só na década de 90 do século passado que se começaram a fazer uma análise política levando em consideração aspectos ambientais como eficiência energética, estabilidade de operação, capacidade de produção. Também se começou a estudar energias renováveis e geração de energia por calor combinado. Foi aí que apareceu o programa Energy2020, criado a partir dos programas mencionados anteriormente. Outros programas também foram criados sobre análise de geração e carga de eletricidade futura para orientar a tomada de decisões políticas. O modelo Treshold21 tem ênfase em sustentabilidade, mas não aborda o mercado de eletricidade.

A parte de ciclos de investimentos e decisões de investimentos começa mencionando Ochoa e van Ackere (2007) na suíça com o decomissionamento de usinas nucleares e mercado de energia. "O resultado mostra que a Suíça necessita de um quadro regulamentar vinculativo a longo prazo para investimentos futuros." Ochoa (2007) em seu outro artigo testa essa possíbilidade e a simulação mostra que o preço da eletricidade pode ser reduzido se forem reduzidos as importações francesas e que ainda é possível lucrar com as exportações italianas.

Na Argentina, Rego (1989) aponta os defeitos da indústria de eletricidade regulada do país. O modelo analisa as variáveis de desenvolvimento retardado e expansão acelerada. Com isso, o preço calculado é baseado na curva de mérito de despacho. O resultado encontrado é a política ideal para solucionar a lacuna das variáveis.

Iniciando a parte de mercados liberais de eletricidade, capacidade de geração, para ser mais preciso, com o tema micro mundos e o artigo de Arango et al. (2002) para analisar os investimentos de capacidade de geração na Colômbia. A incerteza do modelo é posto em variáveis que são calculadas estocasticamente. O resultado obtido no modelo são ciclos de investimentos. A figura 8 apresenta um modelo causal simplificado apresentado por Arango et al. (2002)

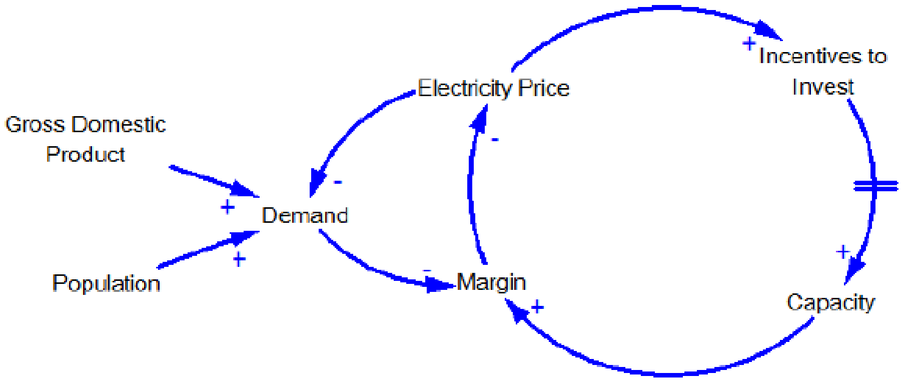

Figura 8: Modelo Simplificado de Mercado de Energia
Fonte: (ARANGO ET AL, 2002)

Gaidosch (2007) faz seu diagrama causal para o mercado alemão. O período de 30 anos escolhido é para simular os investimentos referentes a uma usina geradora de eletricidade. Sua conclusão foi de que “o mercado de eletricidade alemão existente não prevê ciclos de investimento com alta volatilidade.” Sanchez et al. (2008) utilizam a dinâmica de sistemas voltada para a teoria de riscos de crédito e a teoria de jogo econômico. Quanto maior o investimento, maior o empréstimo que será feito. “O modelo é genérico e não é calibrado para um mercado específico.” Ford (1999) avaliou para 5 cenários de construção de usinas geradoras de energia e obteve um resultado cíclico de comportamento de investidores para todos os casos. Syed Jalal e Bodger (2010) estudaram o comportamento cíclico para o mercado de energia da Nova Zelândia.

Pereira e Saraiva (2009, 2010, 2011) utilizaram softwares computacionais e algorítmo genético para seu modelo de dinâmica de sistemas. O sistema permite avaliar decisões para um certo instante no tempo. Olsina et al. (2006) detalham o modelo matemático por detrás do diagrama em seu artigo. Até mesmo as imperfeições de outros trabalhos foram levados em conta, assim como o atraso no investimento de usinas. Bunn et al. (1993) uniram a dinâmica de sistemas com técnicas de otimização para seu modelo de planejamento a longo prazo voltadas a análise de investimentos. O componente chave em seu diagrama é a retroalimentação de capacidade de pagamentos e o principal objetivo, analisar a estrutura do mercado, os riscos e a competição estratégica. Além disso, o autor proclama que o preço não é uma variável confiável no sistema. Larsen e Bunn (1999) listaram os aspectos mencionados e direcionaram os desafios de passar de um monopólio para um mercado competitivo. Gary e Larsen (2000) explicam por diagrama causal o porquê dos sistemas equilibrados alcançarem de imediato o ponto de equilíbrio enquanto os outros modelos não encontram este ponto por conta dos atrasos e das realimentações.

Acevedo e Aramburo (2009) uniu o mercado de energia elétrica com economia experimental para validar seu modelo. Duas variáveis foram definidas para este problema. Enquanto uma produz sua capacidade total, a outra é definida pelo mercado, com a restrição de se usar no mínimo 70% da outra variável. Os resultados indicam que o comportamento cíclico é predominante na variável de utilização total enquanto a outra produz uma tendência fraca deste comportamento. O modelo de Vogstad et al. (2002) simula, em um horizonte de 30 anos, a tendência do mercado de energia nórdica e suas fontes de energia, sendo elas renováveis ou não. Jäger et al. (2009) aprimora o método de Vogstad para o mercado alemão e diz “ser um ponto de partida para discussões do futuro do mercado de energia.”

Outro trabalho de Sanchez et al. (2007) estuda estrutura de oligopólios termos de crédito variáveis dependendo da situação na qual a empresa se encontra. O mecanismo do modelo considera a influência do preço das licitações na compra e venda de energia para se chegar ao preço de equilíbrio do sistema.

Tan et al. (2010) analisam os investimentos de turbinas eólicas. O trabalho une dinâmica de sistemas junto com método de escolha por ramificações de árvore e então faz o caminho inverso para descobrir o resultado da decisão. Qudrat-Ullah e Davidsen (2001) observam o contraste entre a matriz energética do pasquistão ser grande parte fóssil e pouca hidrelétrica apesar do favorecimento geográfico para este tipo de geração. Mesmo com a preocupação com as emissões de dióxido de carbono, a previsão mostra que terá pouca energia renovável no país e bastante combustível fóssil. Com esta preocupação Qudrat-Ullah (2005) apresenta um novo modelo para ajudar a decições políticas com enfoque em desenvolvimento sustentável.

Na classificação de design de mercados, Vogstad (2005) estuda o preço futuro dos certificados de energias renováveis com base em dados históricos e observa qual será a tendência das políticas energéticas futuras. Ford (2006) analisa em diferentes cenários, as consequências da introdução de taxas relacionadas a emissão de dióxido de carbono na atmosfera. Ford (2006) percebeu que quanto maior a oferta de demanda, maior a redução das emissões de dióxido de carbono na atmosfera. Em outro artigo, Ford (2007), aprimorando o modelo de Vogstad, faz previsões para a indústria de energia eólica.

García-Álvarez et al. (2005) trabalham em cima do mercado de eletricidade da Espanha. A conclusão deste artigo foi de “que as principais concessionárias na Espanha podem exercer poder de mercado.” No Reino Unido, Bunn et al. (1997) estudam a participação do gás natural no mercado para a geração de energia elétrica.

Em rede de transmissão e acoplamento de mercado, Ojeda e Garces (2007) escreveram as consequências do mercado no caso de saída de usinas nucleares e aumento da energia eólica. A conclusão do autor é de que a confiabilidade aumenta unindo-se com a reserva do mercado de energia. Ojeda et al. (2009) modelaram um mercado de transmissão de energia elétrica no qual os operadores estão interessados em novas tecnologias e a lucratividade delas. Duas variáveis são analisadas mais profundamente, a capacidade de transmissão e a capacidade de geração. No fim, o resuldado foi de que “os operadores de rede deveriam ter permissão para comportamento estratégico.”

Dyner et al. (2011) e Dimitrovisk et al. (2004, 2007) discutem em seus artigos a estruturação dos modelos de acoplamento de mercado e redes de transmissão além de dar diretrizes para outros autores em seus modelos que visam uma produção mais eficiente. Turk e Weijnen (2002) modelaram uma estrutura genérica de mercado. Sua conclusão foi de que a estabilidade do sistema é alcançada atráves de monitoramento contínuo da performance e medidas apropriadas. Já Hui (2009) foca seu trabalho nos investimentos na infraestrutura da rede de transmissão.

Usualmente, os modelos de mercados desregulados não leva em consideração as incertezas da competição enquantos os mercados regulados não levam em consideração dinâmica competitiva e decições desreguladas. Corrigindo esses defeitos, Botterud (2003) cria um modelo de mercado extensivo com essas circunstâncias visando o resultado ótimo do problema.

Olsina (2005) em seu modelo de mercado estensivo a longo prazo estuda a contribuição de vários mecanismos de mercado para a segurança de suprimento de carga e questiona ainda o porquê do surgimento de comportamentos cíclicos. Sua simulação mostra que para que o preço se mantenha estável, é preciso que as decisões regulatórias sejam acionadas cedo. Sanchez (2009) une métodos de simulação para que seus resultados possam ser mais próximos o possível do real. A explicação de seu modelo é dada em seus artigos anteriores.

Vogstad (2004) prioriza a competição das gerações de tecnologias enquanto deixa em segundo plano a competição das empresas. “O foco de seu trabalho é estudar o suprimento de eletricidade do mercado de energia e suas emissões de dióxido de carbono.” Levando em conta a substituição de energias renováveis no longo prazo, é previsto que aconteça uma elevação nos níveis de dióxido de carbono na atmosfera.

Grobbel (1999) na Alemanha faz um modelo do mercado levando em consideração as restrições da rede e restrições regionais, com isso, aproximadamente 5000 realimentações são contadas no modelo.

Pasaoglu (2006) em seu modelo Liberalized Eletricity Market Microworld (LEMM) toma as decisões do mercado por processos hierárquicos. É possível neste modelo escolher qual tipo de fonte de energia renovável será feito o investimento considerando ainda os impactos ambientais resultantes de cada tipo de fonte. A conclusão do autor foi de que “no mercado desregulado, as imperfeições prevalecem.”

Na última classificação que é aplicação pedagógica e jogos de guerra de negócios, Teufel et al. mencionam os autores já citados que tiveram seus modelos voltados para o ensino e pesquisa.

CAPÍTULO 4

SURVEY SOBRE O USO DE DINÂMICA DE SISTEMAS NO DESENVOLVIMENTO ENERGÉTICO SUSTENTÁVEL

Um dos temas mais estudados nos últimos anos é o desenvolvimento energético sustentável, em especial o uso de fontes alternativas de energia e seus impactos no meio ambiente.

Foi feito este survey analisando a bibliografia publicada entre o ano 1972 e 2018 que tem como principal abordagem o tema aqui proposto. Os 74 artigos analisados foram separados em duas classificações: Emissão de Dióxodo de Carbono e Mudanças Climáticas.

4.1 Emissão de Dióxido de Carbono

Uma das maiores preocupações atuais é com relação a emissão de dióxido de carbono na atmosfera. Os artigos relacionados a emissão de dióxido de carbono dividem-se em:

- Emissão em Geral
- Veículos Alternativos e Políticas Automotivas;
- Aquecimento Residencial;
- Fontes de Energia e Matriz Energética;

4.1.1 Emissão em Geral

Alguns grupos de pesquisadores como Feng et al. (2013), Liu et al. (2015), Mirzaei e Bekri (2017), Xiau et al. (2016), Wu e Xu (2013), Quadrat-ullah (2017) e Cilinskis et al. (2017) fizeram modelos de estimativa do crescimento das emissões de dióxido de carbono na atmosfera nos países estudados, no caso, China, Letônia, Irã e Paquistão. Em todos os modelos, há um crescimento populacional e da indústria que agrava o problema do dióxido de carbono. Os resultados indicam que é preciso uma nova política para que haja uma redução dos gases que aumentam o efeito estufa na atmosfera.

Kunsch et al. (2004) trata em seu modelo o certificado de emissão zero. Esse certificado pode ser vendido para arrecadar fundos para a empresa de geração de energia. Esse artigo usa dinâmica de sistemas para validar a eficiência econômica proporcionada pelos certificados de emissão zero.

Motawa e Oladokun (2015) exploram o modelo de emissão de dióxido de carbono no ambiente doméstico. O trabalho interliga a relação dos habitantes, habitações e o sistema de energia.

A indústria metálica utiliza combustíveis fósseis para fundir os metais, trazendo-os para o estado líquido e então modelar o objeto desejado. Os artigos de Ansari e Seifi (2012), Chen et al. (2014) e Hu e Zhang (2015), estudam para essa indústria emissora de dióxido de carbono, os impactos ambientais que causam, valida seu modelo e chegam a uma solução para o problema. Nesses artigos, a solução encontrada foi utilizar fornos a arco elétrico com o intuito de reduzir a emissão de gases. Ansari e Seifi (2013) também escreveram sobre a indústria de cimento do Irã que é uma das maiores emissoras de gás carbônico do país. Em sua simulação, a alternativa encontrada foi de utilizar combustíveis alternativos nessa indústria reduzindo assim em aproximadamente um quinto o valor do dióxido de carbono nos próximos 20 anos.

4.1.2 Veículos Alternativos e Políticas Automotivas

Para conter a produção de dióxido de carbono, Mediavilla et al. (2013) propõem um modelo de dinâmica de sistemas onde a geração de energia dos combustíveis fósseis, não só a transformação em energia elétrica, mas para outros tipos de energia, seria amenizada com a inserção de veículos elétricos e de biocombustíveis, mas não seriam suficientes para mudar completamente a matriz energética mundial a base de óleo. Laurischkat e Jandt (2018) com base no desenvolvimento sustentável acreditam que veículos elétricos, painéis fotovoltaicos e armazenamento por meio de baterias são uma boa solução para o futuro. A partir dessas variáveis, criaram um modelo técnico-econômico para avaliar o comportamento desses componentes no mercado de longo prazo. Na China, Liang e Zhang (2018) focaram seu trabalho nas baterias dos carros elétricos, como deve ser feita a troca dessas, seu carregamento na rede, a geração da energia que alimenta a fonte, para citar como exemplo. Os resultados desse artigo demonstram que determinando um preço baseado no tempo de uso da bateria para a troca é o que obteve melhor resultado tanto em eficiência energética quanto econômica.

Ainda na China, Liu e Xiao (2018) estudaram como a frota de veículos elétricos vai crescer nos próximos anos dependendo da atuação política do governo. Seus resultados creem que o país contará com, por volta de 4 milhões de novos veículos elétrico até o ano de 2040 caso não haja a intervenção do governo e se houver, esse número dobrará. Esse resultado é bom para o mercado de carbono pois diminuirá a emissão e a demanda desses combustíveis fósseis. Seguindo essa linha de políticas governamentais no ramo de automóveis elétricos, Liu et al. (2015) fizeram um modelo de administração do transporte público e onde poderia melhorar. Para o cenário do desenvolvimento do setor, ajudaria na redução de geração de dióxido de carbono e economia de energia. Para mudança de trajeto, pouco impactou, mas na mudança de tecnologia, a economia foi considerável. O melhor caso individual foi a organização regulamentada e administração de regras de transporte. A união de todos os fatores provou ser a melhor opção econômica de energia e de redução dos gases. Em Taiwan, Cheng et al. (2015) também simularam ações governamentais para o transporte público. Seus três principais parâmetros foram as taxas de combustíveis, o aumento de vagas de motocicletas e o serviço de ônibus como sendo grátis. Os resultados indicam que as duas primeiras opções individuais foram as mais eficientes para a redução da emissão de dióxido de carbono e frear o crescimento do número de veículos no local. Se considerar as três juntas, o resultado é o melhor encontrado para o modelo.

Na Islândia, Shafiei et al. (2015, 2016, 2017) escreveram três artigos relacionados a combustíveis alternativos de veículos na Islândia. No primeiro artigo, é feita uma simulação do desenvolvimento do mercado de veículos a biocombustíveis em dois cenários, um otimista e outro pessimista para um horizonte até 2050. Conclui-se então neste trabalho que a perspectiva otimista tem um melhor desempenho ao longo do tempo, mas um capital inicial mas elevado. No segundo artigo, é feita uma comparação dos veículos movidos por hidrogênio e por eletricidade. O objetivo é que em 2035 não haja mais produção de veículos a base de petróleo. As conclusões são de que os veículos elétricos lideram na parte econômica, mas perdem em mitigar as emissões de gases do efeito estufa. No terceiro artigo há uma comparação entre os dois tipos de veículos já mencionados com a introdução do veículo a biocombustível. As variáveis deste problema são os combustíveis, o preço deles, a demanda, o suprimento e os postos de abastecimento. Novamente, nas análises dos resultados, no termo econômico o veículo elétrico lidera. Para as emissões, o biocombustível é o que possui melhor rendimento para o problema e o veículo a hidrogênio possui a vantagem de ter pouca dependência do mercado externo.

4.1.3 Aquecimento Residencial

Os pesquisadores Szekeres e Jeswiet (2016) utilizaram a dinâmica de sistemas em bombas de calor para aquecimento residencial. Tendo como base a melhoria crescente do desempenho dessas bombas, o modelo proposto prevê uma redução no consumo de energia, e nas emissões de dióxido de carbono caso a geração seja feita por eletricidade ou não se utilizando combustíveis fósseis. Neste raciocínio, Toka et al. (2014) na Grécia fizeram um estudo de caso para a adoção do combustível para o aquecimento seja feito por meio de biomassa ao invés de se utilizar combustíveis fósseis. Os cenários previstos são de adoção de 85% da população até 2030 se não houver intervenção política. Com medidas de incentivo, aceleraria este processo e a meta de redução de dióxido de carbono seria cumprida no prazo previsto. Três outros artigos, de Ziemele et al. (2015, 2016, 2017) fazem três análises se o sistema de aquecimento residencial usual fosse trocado por um de quarta geração. A primeira análise visa o aspecto econômico e o a eficiência energética para o lado do consumidor. A segunda análise é feita para a troca de combustíveis renováveis no aquecimento. Os resultados demonstram que a redução de dióxido de carbono é de quase 60% sem intervenção política. Dependendo dos incentivos adotados, crê-se que é possível atingir a zero emissão de carbono na atmosfera. A terceira é uma análise de benchmarking com as tecnologias atuais no país. Os resultados indicam que é possível realizar a troca dos equipamentos por outros da quarta geração e ter uma redução nas emissões de carbono.

4.1.4 Fontes de Energia e Matriz Energética

As fontes de energia e matriz energética se classificam em dois grupos, que são, mercado de energia e matriz energética e fontes de energia

4.1.4.1 Mercado de Energia e Matriz Energética

Blumberga et al. (2014, 2016) escreveram dois artigos com diferenças de dois anos, controversos sobre o desenvolvimento do setor elétrico da Letônia. No artigo mais antigo, diz-se que se continuasse com a política de investimentos da época, o gás natural ainda seria forte na matriz energética, mesmo com a redução de quase 30% de dióxido de carbono na atmosfera. No artigo mais recente, esses dados são diferentes, acredita-se que com a política de 2016 possa se alcançar 70% de redução das emissões desses gases e que a matriz será fortemente renovável.

O contrato de oferta padrão, conhecido na língua inglesa por Feed-in Tariff é tema de pesquisa em dois artigos, o de Shahmohammadi e Yusuff (2015) e o de Yu-zhuo et al. (2017). A primeira dupla de autores citados estuda esse contrato nas energias renováveis da Malásia no período de 2011 até 2030, e teme uma escassez nos investimentos caso o valor dessa tarifa se mantenha o mesmo. Esse modelo pode ser utilizado para gerenciar os investimentos, encontrando a melhor forma de se obter a regularidade deste setor. No segundo artigo, os autores, criam um modelo relacionando essas tarifas com as energias renováveis e fazem um estudo de caso com a energia eólica na China. No artigo, também é fornecida opções de políticas energéticas para o caso estudado, além de dar uma base para outros artigos que possam vir no futuro.

Na Coréia do Sul, Sim (2018) obteve a conclusão de que as energias renováveis estão diretamente ligadas à redução dos gases de efeito estufa e ao valor de investimento das energias renováveis. Na Turquia, Saysel e Hekimoğlu exemplificaram a geração das energias renováveis por meio de dinâmica de sistemas na matriz energética do país. O artigo serve de base para estudar os problemas nacionais relacionados ao dióxido de carbono. Vestrucci et al. (2016) abordam a matriz energética italiana. Com os dados de capacidade instalada e de geração, observa-se que uma boa solução para reduzir a geração térmica seja de se adicionar usinas nucleares no país. Outro artigo de matriz energética, agora no Chile foi o de Gómez et al. (2017). Eles afirmam que a matriz chilena é bem robusta e que precisa de novas políticas de apoio às renováveis. Um estudo de transição de matriz energética tradicional para uma matriz energética mais renovável foi desenvolvido na Suécia por Tang e Rehme (2017). Neste trabalho é dito que as políticas energéticas não devem operar sozinha, mas junto com incentivo às energias renováveis e o decomissionamento de usinas nucleares. O modelo de Blumberga et al. (2016) acredita que o mercado das energias renováveis é promissor na região báltica exceto o do biogás. Aslani et al. (2014) tiveram sua contribuição na dinâmica de sistema para a Finlândia. Seu modelo sugere políticas de incentivo às energias renováveis voltadas à segurança energética do país. Mais uma vez, Aslani jundo de Wong (2014) estuda a matriz energética, mas dessa vez para o caso do custo de geração das energias renováveis dos Estados Unidos. Seus resultados mostram que as energias renováveis criarão um mercado de 10 bilhões de dólares em 2030. Bodger e May (1992) desenvolveram um modelo de dinâmica de sistemas para a matriz energética da Nova Zelândia e onde o mercado dos combustíveis fósseis se enquadra no modelo. Liu e Zheng (2017) na China criaram um modelo para avaliar os riscos da implementação de uma matriz energética com combustíveis não-fósseis. Os resultados indicam que o risco político é o que mais interfere para a maturidade da matriz energética. O trabalho de Moallemi et al. (2017) mostra a transição para uma matriz de energias renováveis na Índia, ele primeiro descreve toda a estrutura do setor, como funciona para depois exemplificar com seu modelo de energia solar e eólica. A nação suíça é outra no modelo de matriz energética renovável desenvolvida por Osorio e Ackere (2016). Sua intenção é trazer mais painéis fotovoltaicos para o país e tirar de operação algumas usinas nucleares, além de utilizar energia hidráulica como uma bateria.

A emissão de dióxido de carbono residencial também é palco de estudos nos modelos de Robalino-lópez et al. (2014) e de Bernardo e D’alessandro (2016). Para o primeiro modelo, os equatorianos acham a solução de energias alternativas e uso mais eficiente dos combustíveis fósseis. No segundo artigo, a análise é econômica com os resultados de três alternativas, redução direta nas emissões de carbono, desenvolvimento das energias renováveis e eficiência energética.

O artigo de Shih e Tseng (2014) estima os benefícios da política de sustentabilidade energética e energias renováveis separadamente. Seus resultados indicam que a política de eficiência energética é menos benéfica do que a de energias renováveis.

Unindo o modelo de Monte Carlo com micro e macro fatores da dinâmica de sistemas, Jeon e Shin (2014) apresentam neste artigo um novo método para decisões de pesquisa e desenvolvimento tanto para o setor público, quanto para o privado.

Pensando como em planejamento da operação e expansão do setor, Pina et al. (2011) trazem para a dinâmica de sistemas as ferramentas temporais utilizadas nesse planejamento. O modelo validado em Portugal compara o resultado pela dinâmica de sistemas e os dados reais do sistema. A partir das análises do resultado, algumas sugestões de políticas energéticas renováveis são feitas.

4.1.4.2 Fontes de Energia: Nuclear, Térmica, Biogás, Eólica, Maremotriz e Solar

Antes de se pensar em reduzir as emissões de gases do efeito estufa, Kunsch e Friesewinkel (2014) criaram um modelo de segurança energética por conta de remoção de 7 usinas nucleares na matriz da Bélgica. A resposta mais rápida para o problema foi de se adicionar usinas térmicas na intenção de solucionar este problema. Todavia, a Bélgica fica refém dos preços do mercado externo e agrava o problema das emissões de gás carbônico no país.

Naill (1976) em 1976 acreditava no crescimento do mercado de óleo dos Estados Unidos e criou assim um modelo que projeta o crescimento a indústria de óleo do país até se tornar independente externamente dessa fonte de energia.

Quatro anos antes dessa data, Nail (1972) em seu trabalho, apresenta um estudo em dinâmica de sistemas do aspecto econômico em cima dos combustíveis fósseis para os americanos do norte. Em seu modelo, ele explica a curva de crescimento e declínio do preço desses combustíveis e avisa que é preciso uma regulamentação nesses preços. Abada et al. (2013) aperfeiçoaram um modelo de preços do gás natural. Este modelo é calibrado para se determinar o preço do gás natural na geração de energia com as variáveis mais fiéis ao real. Chi et al. (2009) apresentam um modelo de demanda para a indústria de gás natural indígena do reino unido. Dependendo da política de subsídios adotada, pode ocorrer uma aceleração precoce no crescimento do setor ou uma aceleração mais suave tardia.

Em 2004 na Noruega, Vogstad (2004) faz um survey dos métodos já publicados do sistema de aquecimento residencial por carvão e por gás natural. Sua pesquisa mostrou que não era possível agradar o lado econômico e o lado ecológico ao mesmo tempo. Sua previsão é de que o gás natural substituiria o carvão a curto prazo, reduzindo na emissão de gás carbônico, mas o mesmo gás natural substituiria as fontes renováveis de energia e agravaria ainda mais o problema com o dióxido de carbono no longo prazo.

Dois artigos citam a Letônia e a utilização de biometano para a produção de energia. Romagnoli et al. (2014) em seu artigo, cita o biometano como forma alternativa de combustível para o setor de aquecimento urbano e menciona ainda que políticas de incentivo são essenciais para o desenvolvimento deste setor. Já Repele et al. (2017) não se limita ao setor urbano, acredita que o biometano possa ser um substituto para o gás natural no futuro. Para que este cenário ocorra, uma boa parcela de investimento na tecnologia do biometano deve ser feita.

Outro artigo de Repele et al. (2016) propõe um modelo de crescimento estável do biometano na matriz energética evitando assim, oscilações muito positivas e muito negativas no tempo proposto. Os resultados previstos indicam que é possível chegar a 610 GWh de produção de energia em 2030 caso tenha um investimento de 66 euros por MWh.

Mutanga et al. (2016) descreve em seu artigo um modelo de bio-refinaria para geração de energia elétrica. Utilizando de lixo, biogás e reaquecimento, os resultados mostram que o a eficiência dessa geração é melhor e mais ecológica do que as refinarias usuais.

A energia eólica também foi palco para estudos de viabilidade. Esmaieli e Ahmadian (2018) desenvolveram um método abordando dinâmica de sistemas para o desenvolvimento da energia eólica que não produz gases de efeito estufa em sua geração de eletricidade.

Outra Tecnologia que não gera dióxido de carbono em seu funcionamento é a transformação da energia cinética das ondas para eletricidade. O estudo feito por Burcher et al. (2016) visa entender o porquê da desmotivação dos investidores nessa tecnologia. Os resultados indicam que caminho deve ser tomado para que os investimentos na geração de maremotriz possam crescer para esta tecnologia alcançar a maturidade.

Ma et al. (2010) estudaram o hidrogênio na matriz energética chinesa. Sua conclusão foi de que o setor secundário da indústria, deve ser provido de projetos de pesquisa e desenvolvimento de energia. A mudança de demanda de hidrogênio não é eficaz, isto devido ao crescimento da economia chinesa e outros fatores.

O artigo de Sisodia et al. (2016) na Índia, faz um estudo utilizando dinâmica de sistemas para a implementação de energia solar a nível nacional. O método faz a interligações das variáveis da energia solar e seu resultado é o que é necessário para que haja aceitação de energias renováveis no país.

Na Espanha, Movilla et al. (2013) descreve como o mercado fotovoltaico age com os investimentos atuais e indaga se no futuro, este mercado será autossustentável sem a política de intervenção do governo no suporte financeiro. Utilizando dados históricos dos anos passados, um modelo foi desenvolvido a fim de ajudar a desenvolver futuras políticas de investimento.

Já na Alemanha, o problema é o contrário. A equipe de Baur (2018) pesquisou um método com a dinâmica de sistemas para frear os incentivos dos investimentos nos painéis fotovoltaicos do país. O modelo testa várias políticas de investimento para geração residencial de energia elétrica proveniente da energia solar. A conclusão é de que é possível criar uma política assim e ainda serve de exemplo para outros países.

4.2 Mudanças Climáticas

Outro problema preocupante são as mudanças climáticas causadas pelo efeito estufa. Petersen et al. (1992) publicaram um artigo pelo Departamento de Energia dos Estados Unidos utilizando modelo de energia integrado FOSSIL2 para mitigar o problema do aquecimento global. Esse modelo visa criar soluções para a redução da emissão dos gases estufa que agravam o aquecimento global e quais os custos associados. Na Austrália, Sahin et al. (2017) perceberam que estava acontecendo uma mudança climática local envolvendo o abastecimento de água e crescimento populacional na região. Para que a escassez de água fosse controlada e não prejudicasse o microclima local, um modelo de dinâmica de sistemas foi construído para mitigar o problema em um horizonte de 100 anos. Os resultados dessa pesquisa indicam que a melhor solução para o problema é a tecnologia de osmose reversa das plantas, que é uma tecnologia sustentável.

O modelo ANEMI_2 criado por Akhtar et al. (2013) com abordagem em dinâmica de sistemas permite a modelagem de mudanças globais complexas e ainda fornece ideias de soluções para essas mudanças. Este modelo possui nove variáveis que interferem diretamente no problema de mudança climática, e leva em consideração os principais gases que influenciam no efeito estufa. Os resultados são conforme o esperado pela literatura científica além de sugerir opções para mitigar esse problema.

Ansell e Cayser (2018) com base no modelo World3 da grande pesquisadora Meadows e sua equipe, desenvolveram o Modelo de Energia Global alterando as variáveis de recursos e poluição genérica por geração de energia e mudança climática. O estudo investiga o aspecto socioeconômico voltado para a variável de mudança climática e os reservatórios de combustíveis fósseis. As projeções para 2100 são um aumento de 2,4 a 2,7 graus celcius na temperatura média global e um aumento de 50% no custo de produção de energia. Os pesquisadores acreditam que os resultados desse modelo são mais estáveis do que seu antecessor.

Em 2002 Fiddaman (2002) faz um modelo integrado energético-econômico para mudanças climáticas. Segundo o autor, os modelos energéticos até o momento não representavam próximo da realidade as mudanças climáticas por falta de variáveis econômicas como as taxas de carbono do protocolo de Quioto por exemplo. Os resultados dizem que quase todas as opções políticas levam a um benefício líquido e que as decisões escolhidas atuais são mais perdoáveis do que se acredita.

CAPÍTULO 5

CONCLUSÃO

Tomando-se como base o objetivo deste trabalho, isto é, mostrar como a técnica de simulação computacional conhecida como Dinâmica de Sistemas tem sido usada por pesquisadores do mundo todo na abordagem da complexidade da tomada de decisões na área energética, pode-se dizer que atingimos tal meta através das seguintes contribuições:

1. Levantamento bibliográfico sistemático das principais publicações com modelos de sistemas de energia em geral que usam como ferramentas de análise as técnicas (qualitativas e quantitativas) desenvolvidas por Jay Forrester e denominada Dinâmica de Sistemas.

Destacam-se nestes achados dois *surveys* que mostram de uma forma bem abrangente o conhecimento nestas áreas:

- Ahmad et al. (2016) - **Application of system dynamics approach in electricity sector modelling: A review.**
- Teufel et al. (2013) - **Review of System Dynamics models for electricity market simulations.**

2. *Survey* sobre o **Uso de Dinâmica de Sistemas no Desenvolvimento Energético Sustentável**, visando suprir uma falha nos *surveys* de Ahmad et al. (2016) e Teufel et al. (2013) sobre questões de sustentabilidade, hoje uma das principais preocupações e tendências quando se trata do desenvolvimento dos sistemas energéticos.

Acredita-se que este trabalho possa vir a despertar o interesse de outros colegas, pois a técnica de simulação conhecida como Dinâmica de Sistemas tem sido bastante usada para trabalhar com situações complexas que envolvem especialistas de diversas áreas e que normalmente têm dificuldades de comunicação entre si. A criação de modelos brasileiros, qualitativos e quantitativos (modelagem no software Inside Maker), em linhas de transmissão, planejamento da expansão, planejamento da operação e o crescimento das energias solar e eólica são alguns exemplos de trabalhos futuros.

Por se tratar de uma técnica de análise em dois níveis, um **qualitativo (através dos diagramas causais)**, e outro **quantitativo (através dos diagramas de estoque e fluxo)**, esta abordagem é bastante amigável, pois emprega linguagens de aprendizado acessível e rápido, ao alcance de profissionais de diversas áreas. Isto é importante quando se trata de analisar sistemas sustentáveis de energia onde atuam profissionais de várias áreas e é imperiosa a necessidade de ferramentas de análise capazes de se serem entendidas de forma clara e objetiva por todos.

Outro ponto interessante a se observar no estudo é o número de publicações por fonte dentro da bibliografia listada nas referências. Dos 74 artigos referenciados, destacam-se na tabela abaixo alguns periódicos que normalmente ficam fora do universo de publicações mais tradicionais dos pesquisadores na área da Engenharia Elétrica. É de se observar que nenhum dos artigos foi publicado nas revistas do IEEE.

FONTE	**Artigos**
Energy	16
Energy Policy	10
Applied Energy	9
Journal of Cleaner Production	9
Energy Procedia	5
Technological Forecasting and Social Change	3
Renewable and Sustainable Energy Reviews	2
Renewable Energy	2
System Dynamics Review	2
Ecological Indicators	1
Ecological Modelling	1
Energy and Buildings	1
Energy Conversion and Management	1
Energy for Sustainable Development	1
Environmental Innovation and Societal Transitions	1
Environmental Modelling & Software	1
Environmental Research	1
European Journal of Operational Research	1
International Journal of Hydrogen Energy	1
International Journal of Production Economics	1
Oxford University	1
Procedia CIRP	1
Procedia Computer Science	1
Sloan School of Management, MIT	1
Thayer School of Engineering, Dartmouth College	1
TOTAL	74

Tabela 1: Frequência de distribuição por fonte dos artigos listados nas Referências

Fonte: (Elaboração Própria).

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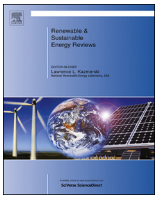

Application of system dynamics approach in electricity sector modelling: A review

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System dynamics

ABSTRACT

Electricity has become a vital source of energy for social and economic development in modern era. Likewise, the issues of its planning and management have grown complex. To address complexity in decision making, researchers have chosen system dynamics (SD) modelling and simulation technique. A state-of-art of such studies published during the period 2000–2013 is presented in this paper. The contribution of this review lies in categorizing the literature based on the important and contemporary researched areas. These research areas include models developed for policy assessment, generation capacity expansion, financial instruments, demand side management, mixing methods, and finally micro-worlds. Review shows that policy assessment and generation capacity expansion are the two most modelled topics. Financial instruments models evaluate different mechanism to support renewable technologies whereas mixing-methods channelize descriptive approach of SD into evaluating a single objective. Demand side management and micro-worlds are the least focused categories in SD. This paper also discusses the individual models in each category highlighting their construct, outcomes and any deficiencies.

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1. Introduction

Energy planning has been classified as a complex issue due to its interaction with other sectors of the society [1]. These interactions include production, demand, technology, fuel security, affordability and environmental concerns. With an increasing dependence of modern society on energy, a myriad of models have been developed to facilitate energy planning process. The aim of these models is to understand and analyse the complexity surrounding the energy issue so that not only resources are managed efficiently but also demand is met adequately with minimal damage to environment. These models come from disciplines like economics [2,3], operational research [4–6], and social sciences [7,8]. Jebaraj and Iniyan [9] reviewed energy models in the literature, and grouped them as follows: energy planning, energy supply–demand, forecasting, optimization, neural networks and fuzzy theory based ones. Bazmi and Zahedi [10], Baños et al. [11], and Foley et al. [12] reviewed optimization-based models for energy system planning. Furthermore, Connolly et al. [13] reviewed computer simulation models that allow analysis of integrating renewable energy sources. This review paper is distinct from previously mentioned ones as it reviews models particularly developed using System Dynamics (SD) approach.

In this review, only one form of energy, electricity, is focused. The reason for this emphasis is because electricity is the newest form of energy human society has embraced [14]. Also, the demand of this commodity has increased at a dramatic pace of 3.5% annually [12]. Moreover, due to its importance, electricity has been the prime focus of many energy related studies as well [15]. Beside this, to maintain a secure, reliable and affordable supply of electricity, decision making process in the sector has become a challenge for investors and policymakers, alike, due to uncertainties surrounding electricity sector. The sources of uncertainties are: (i) delays in generation and related infrastructure construction; (ii) choice and advancement in technology; (iii) resources limitation; (iv) price and demand fluctuations; (v) pollution and environmental concerns, and, last but not least, (vi) regulatory and political issues. Further, electricity sector is dynamic in nature; it is continuously evolving over time. The aforementioned sources of uncertainty are also inherently dynamic in nature. The decision making landscape becomes even more intriguing when a competitive electricity market structure is considered [16].

As proposed by McIntyre and Pradhan [17] while developing any decision making model in electricity sector, a holistic approach must be adopted. This requires that not only technical but also social, economic and environmental issues to be considered. The well-known models like MARKAL/TIMES, LEAP, WASP, EGEAS, MESSAGE, RETScreen and many more, rooted in the above mentioned disciplines, do adopt a holistic approach but ignore feedbacks, delays and nonlinearities related to factors being modelled. Furthermore, non-SD models rely on equilibrium or energy balance framework. This assumption in long-run cannot be maintained. The reason for this shortcoming is the continuously evolving nature of social, economic, environmental and technological factors involved. To cater for the deficiencies, researchers resolved to SD approach of modelling, analysis, and evaluation. SD approach has a number of merits over other modelling approaches. This includes:

1. Allowing researchers to model complex energy system from cause-effect perspective, rather than relying on statistically significant relationships;
2. Enabling a modeller to identify feedbacks which enrich analysis capabilities of the model; and
3. Relaxing the linearity hypothesis, thus allowing modellers to include nonlinear relationships.

Over years numbers of researchers have used SD to model electricity sector. Therefore, there is a need to glean information on those models.

The layout of this paper is as follows. Section 2 describes the objectives and research design, followed by a brief introduction of SD methodology in Section 3. Section 4 reviews in detail the studies done using SD. The paper concludes with major findings in Section 5.

2. Objectives and research design

The motivation of this survey is to highlight SD contribution to electricity sector modelling. The objectives of this research include: (i) to review electricity sector modelling done using SD and (ii) to serve as a critical reference on issues and construct of those SD models. The period of interest for this review started in January 2000 and ended in December 2013. The choice of time period is based on the fact that a review prior to 2000 has been published by Ford [18]. A year by year search was made on Elsevier SCOPUS, Springerlink, and EBSCOhost online databases using key phrases. The key phrases used were: SD and electricity, computer simulation and electricity, electricity and policy modelling. Each database search was then limited (discipline wise) to full length peer-reviewed articles. Conference papers, communications, and book reviews, master and doctoral theses were excluded. Selection of articles was limited to journal articles only because journal article represent the top-echelon of research [19]. Scrutiny of articles resulted in 55 papers of which 35 fall under the scope of this review. Table 1 shows the distribution of reviewed papers by journals.

With the design intent in mind, SD and electricity sector, individual articles were reviewed thoroughly to identfy the focus, uniqueness, any shortcomings. Each article was then grouped in the 'most appropriate' category and before comparing it with other papers within the same category.

3. System dynamics modelling approach

The modeling and simulation method of SD was first developed by Prof. J.W. Forrester, MIT, in 1950s to analyze complex behaviors in social sciences, distinctively in management, through computer simulations [20]. Prior to the SD, decisions made to tackle a problem often resulted in unexpected outcomes; hence there was a pressing need for developing a new methodology [21]. This counter intuitive behavior of the system is attributed to the

Table 1
Distribution of reviewed papers by journal.

Journals	Number of papers reviewed
Energy Policy	13
Energy	5
Renewable Energy	2
Socio-Economic Planning Science	2
International Journal of Electricity Sector Management	2
European Journal of Operations Research	1
International Journal of Critical Infrastructures	1
International Journal of Simulation	1
Simulation Modeling Practice and Theory	1
Sustainability	1
System Research and Behavioural Science	1
System Dynamics Review	1
Ecology and Society	1
Applied Energy	1
IEEE Systems Journal	1
Kybernetes	1

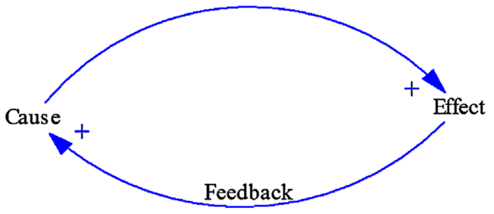

Fig. 1. The Causal loop diagram. Adapted from [21].

Table 2
Basic building blocks used in system dynamics with icons. Adapted from [20].

Building block	Symbol	Description
Stock (level)	□	It shows an accumulation of any variable.
Flow (rate)	⧖	Attached to a stock. Alters stock level by an inflow or an outflow
Auxiliary(convertor)	○	Connects stock and a flow in a complex setting. Used for intermediate calculations.
Connector	→	Link different building blocks, showing the causality

structure in which they are influencing each other, rather than to the variables of the system [21,22].

SD modelling process starts with problem articulation to determine the boundary of the system. Causal loop diagrams are then drawn with major variables linked together in feedback fashion. Causal loop diagram (CLD) links system variables by arrows. These arrows show the direction of influence while the polarity accompanying arrows depicts the effect of influence: positive for direct, and negative, for an inverse influence. A CLD schematic is depicted in Fig. 1. A mathematical stock and flow diagram (SFD) is then developed for simulation purpose followed by a testing phase. The final stage of modelling process is policy design and evaluation. This stage consists of 'what-if' analysis and sensitivity tests.

To develop a quantitative SFD from qualitative CLD, four building blocks are used: stock, flow, auxiliary, and a connector (see Table 2). A stock shows the level of any system variable at a specific time instant and can be of two kinds: tangible or intangible. Tangible stock includes natural stocks, goods or capital, whereas intangible stock can be information, psychological or any indexed value. Flow or 'valve' is attached to a stock. Flow is responsible for increasing or depleting stock's level. An auxiliary or a converter can be parameters or values calculated from other variables within the system. Finally, a connector or an arrow denotes connection and control between system variables.

In Fig. 2, an SFD built in iThink® shows the icons used for various building blocks. The cloud icons that are at the start and at the end of the inflow and the outflow represent the system's boundary.

4. System dynamics and electricity sector modelling

In this section, a review of models using SD methodology is presented. The categorical distribution of articles is presented in Table 3.

4.1. Policy assessment models

A policy assessment model evaluates an intended or implemented policy in a country. These models investigated support policy for private investors [23,24]; policies for power market deregulation [25–27]; cross-border trading of electricity [28,29]; comparing policies to promote renewable power sources reducing dependency on fossil fuels [30–33], and environmental savings [34].

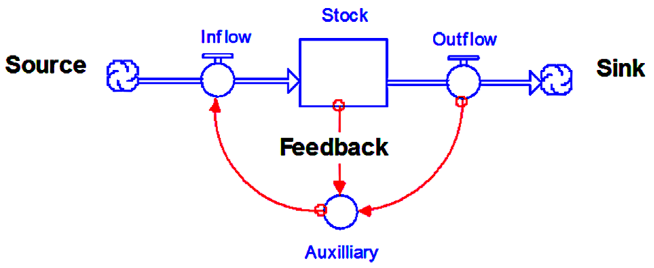

Fig. 2. Stock and flow diagram in iThink®. Adapted with modification from [21].

Table 3
Distribution of reviewed papers by categories.

Categories	Number of papers reviewed
Policy Assessment	12
Generation Capacity Expansion	9
Financial Instruments	5
Mixing-methods	3
Demand Side Management	4
Micro-Worlds	2

By anticipating the effect of changing policies on the electricity market, Qudrat-Ullah and Davidsen [23] developed an SD model of electricity generation sector of Pakistan. The model investigated the impact of government's policy of boosting private sector investments in power generation. Demand, investments, resources, production capital, production, environmental, and finally the financial sub-sectors were modelled. The interaction of these sub-sectors with the Gross Domestic Product (GDP) driving electricity demand was assumed to produce dynamic behaviour of industry. The model simulations revealed that government's continuous support to Independent Power Producer (IPP) resulted in fossil-fuel based capacity investments, and consequently CO_2 emission. Simulations further revealed that with a new policy in place, hydroelectric development would be impeded. The model effectively showed the side effects of a policy. However, overly relying on a single exogenous variable (GDP) as the driver of long-term demand seems not that appropriate. Other macro-economic factors, like population and electrification rate could be more appropriate for inclusion in a model of a developing country. With similar sub-sectors and policy focus, the study by Qudrat-Ullah and Karakul [24] revealed that investments in generation sector seemed not sufficient to meet the growing demand in the long-term. Though both studies model revealed ramifications of new policy effectively, they ignored any environmental or demand reduction measures on the system. Further, both of these studies ignored renewable technologies for power generation, apart from large hydropower. In addition, future investments were made dependent on the identification of a least-costing technology (also adopted by Pasaoglu Kilanc and Or [26]). This narrowed down the scope of technology evaluation as oppose to one from multi-perspectives, which is more holistic.

In the back-drop of electricity industry deregulation, Kilanc and Or [27] developed a model to observe the future composition of Turkey's electricity generation sector. Though the model has similarities in model sub-sectors to Qudrat Ullah and Davidesn [23] and Qudrat-Ullah and Karakul [24], however, investors were divided into three categories: incumbent, IPPs, and new entrants. Also, a bidding mechanism for export of electricity to grid was introduced. The model was capitalised by Pasaoglu Kilanc and Or [26]. Simulation exposed the imperfect foresight of investors in decision making and power plant construction delays resulting in generation capacity and electricity price fluctuations. A technology lock-in to natural gas and hydropower plants was also observed. Moreover,

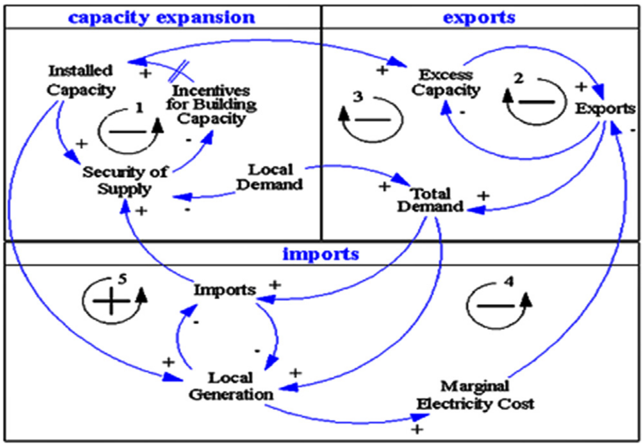

Fig. 3. Causal loop diagram to model Swiss. Source [29].

despite government's support, simulations showed under investments in wind power and no explanation for this finding was provided. Further, no mechanism was provided in the model which could avoid market power of investors. This shortcoming was highlighted in simulations when generation companies can decide to withhold their capacities, subsequently raising electricity price.

Set in a regulated electricity market, Ochoa [28] presented a qualitative SD model for Switzerland. A CLD was developed to identify the repercussions of different policies. Particularly, the model was concerned with identifying the influence of nuclear power phase out and bilateral electricity exchanges on installed generation capacity and electricity price. On the basis of the conceptual model, the author claimed that withdrawing nuclear power from supply chain would not only increase import dependency but also electricity price. In case policy bans import, only then capacity expansion could be expected ensuring security of supply and earning from export of electricity. The qualitative model ignored the environmental and transmission network constraint of the system along with considering renewable technologies for power generation. Ochoa and van Ackere [29] expanded the scope of Ochoa [28]. Simulation demonstrated that international electricity exchanges were essential for meeting demand, keeping cost of electricity low and in generating income for utility companies. In case of a nuclear phase out, simulations revealed that the capacity gap could only be filled by gas based technologies. Fluctuations in generating capacity were observed in model's output, similar to Pasaoglu Kilanc and Or [26]. The study elaborated the model through CLD only and the lack of any description of mathematical formulations used. The CLD used by Ochoa and van Ackere [29] is shown in Fig. 3.

Stemming from the sustainability framework, Cimren et al. [30] developed a model to analyze waste-to-electricity policy for Ohio, USA to curb CO_2 emissions as well as its potential in creating new jobs. Incorporating job creation in the model was a novel idea used in this study. This was in contrast to Qudrat-Ullah and Davidsen [24], Pasaoglu Kilanc and Or [26], and Ochoa and van Ackere [29], who focused more on economics of technology and meeting demand as the prime factors for selecting a technology. The analysis found that the said policy not only reduced greenhouse gases but it also created new jobs. Though results were presented in the paper, model development was significantly lacking in the study. Also, the study assumed all available biomass to be co-fired with coal for power generation while neglecting other uses of biomass, for example, as fertiliser. Furthermore, split between biogas and biomass for electricity generation was neglected in the model.

Zhao et al. [31] model focused on assessing two incentive policies for promoting solar photovoltaic (PV) in residential sector. These policies included investment tax credit (ITC) and feed-in tariff (FiT). The developed model used Bass model of technology diffusion at its core. However, the introduction of two new variables, i.e. the payback period of investments, and the household monthly income extended the classical Bass model. Unlike Qudrat-Ullah and Davidsen [23], the driver of increasing demand was not made explicit. The model pivoted on calculating the payback period for investment decision which was then used in macro-level setting to highlight the PV adoption process. Simulations showed that an incentive policy did sped up the technology adoption process. However, no significant difference was found between either policy-FiT or ITC. On methodological side, the study lacked presenting feedback structure used in relating both policies. Also, the model treated solar PV technology as a mature technology with no link to cost reduction (either by using technology or by technology advancement) as the one studied by Hsu [35].

Despite the interdependency of electricity and water, there is a lack of frameworks guiding policy developments [36]. To encourage researchers to deal with this issue, Newell et al. [32] proposed a qualitative SD model for Australia. The issues of water scarcity, emissions and electricity production were dealt with in the model. Unlike Elias [37] who relied on focussed groups, this study used secondary data to highlight the problem through various CLDs. On the contrary to Qudrat-Ullah and Davidsen [23], Cimren et al. [30] and Saysel and Hekimoglu [34], the study included the issue of food security related to electricity production through water scarcity, not just CO_2 emissions. However, in the same way as Pasaoglu Kilanc and Or [26], the study modelled imperfect foresight of decision-makers in dealing with the issue. The study proposed to policy makers to readily change the structure of Australian market and increase cross sector dialogue in dealing with electricity and water issues comprehensively. In comparison to Ochoa [28], the CLDs presented lacked coherence. Furthermore, no proper justification was given for electrification of transport sector as the only factor for an increase in electricity demand. Electricity demand can be modelled by many macro-level indicators like, population, changing life style and economic growth of the country. Also, the study excluded consideration of renewable technologies for power generation which are very pertinent to policy-makers in the described scope of work.

Ahmad and Tahar [33] presented a model that assessed renewable capacity target for five different technologies in Malaysia. The model relied on modelling delays in planning and construction while ignoring how various factors (e.g. demand, cost, reserve margin etc.) influenced investment decision as modelled by others (see Refs. [23,24,34]). Though the findings were very useful for future policy development, the lack of feedback between capacity expansion plan and cost of technology made the model to be less dynamic.

Fuentes-Bracamontes [25] developed a model named REFELECTe. The model focussed on Mexican electricity generation sector only in the context of deregulation policy. Like Qudrat-Ullah and Karakul [24], the model used demand, price, investment-decision and environmental sub-sectors. The main driver of the model- electricity price- was modelled as follows in Eq. (1).

$$\text{electricity price} = f(\text{fuel cost},\ \text{reserve margin}) \tag{1}$$

The output of the model revealed that the competition in fossil-fuel technologies-while keeping the control of hydro and nuclear capacity with the government-achieved environmental and security of supply target, along with keeping the price within acceptable range. Unlike Qudrat-Ullah and Davidsen [23] and Qudrat-Ullah and Karakul [24], REFELECTe used IF-THEN-ELSE statements for choosing between various generation technologies being modelled. This approach, though simple and less computational, served the purpose effectively. The model assumed future capacity investments as a function of capacity retirements. This setting ignored capacity investments which were needed due to rise of demand. REFELECTe's algebraic equations were provided but the lack of causal

Table 4
Policy assessment model summary.

Model focus	Reference	Weakness
Deregulation	Fuentes-Bracamontes [25]	Ignored capacity investments due to rise in demand
	Pasaoglu Kilanc and Or [26]	Formulation to limit market power of competitors was not modelled
	Kilanc and Or [27]	Sparse description of mathematical model
Support policy for private investors	Qudrat-Ullah and Davidsen [23]	Overly relying on one variable for driving the model
	Qudrat-Ullah and Karakul [24]	Environmental ramifications were being ignored
Environmental saving	Saysel and Hekimoglu [34]	Social and technological advancement were ignored
Cross-border trading of electricity	Ochoa [26]	Reference- mode behaviour of key variables was not provided
	Ochoa and van Ackere [27]	Environmental and transmission network constraints were ignored
Promote renewable power sources	Cimren et al. [30]	Other uses of biomass were ignored
	Zhao et al. [31]	An analysis of combination of two incentive policies was neglected
	Newell et al. [32]	Integration of concept was difficult due to lack of coherence between various models
	Ahmad and Tahar [33]	Narrowly focussed model on policy target

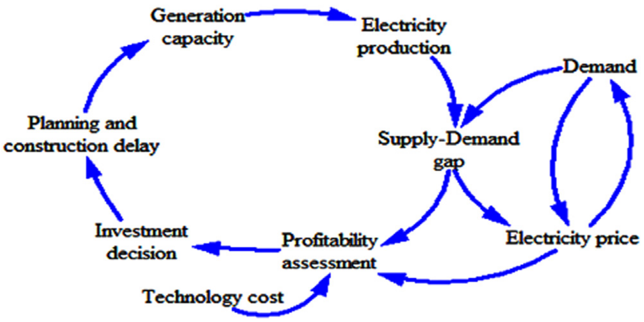

Fig. 4. Generic causal structure used in GCE models.

loop diagrams undermined the confidence in the model. Finally, assuming an accelerated depreciation of a power plant on the basis of underutilization seemed an unrealistic assumption. Though a particular technology power plant may be lower in the merit-order of scheduling, dismantling it before the lapse of its useful life was uneconomical, as power plants have almost no salvage value [38].

In a study undertaken by Saysel and Hekimoglu [34], contribution to carbon mitigation policy by electricity generation from renewable resources was discussed. The model allocated future demand onto five renewable and two fossil-fuel technologies based on the cheapest production cost basis. The same approach of choosing a particular technology has been adopted by Qudrat-Ullah and Davidsen [23] and Fuentes-Bracamontes [25]. Though logical, this approach failed to account for externalities (e.g. social and technological advancements) in renewable technologies. In addition, the study assumed capacity replacements prompted by price driven incentives, like Fuentes-Bracamontes [25], which was also not possible as power generation technologies were capital intensive with almost no salvage value. The study showed that emission reduction policy can be successful, if power generation was shifted to renewable resources.

The models used for policy assessment are summarized in the Table 4.

4.2. Generation capacity expansion models

Articles falling under this category comprise of models that were developed to address the generation capacity expansion (GCE) problem in the electricity sector. GCE decision is crucial to decision makers as the entry and exit barriers in power generation sector are high. Therefore, vigorous analyses are needed before committing to generation capacity expansion. The main focus of GCE models was to find out which technologies for power generation will constitute the system in a long-run i.e. in the context of being the most profitable as well as serving the demand. Some GCE models investigated multi technologies (e.g. Olsina et al. [38], Hasani-Marzooni and Hosseini [39] and Qudrat-Ullah [40]), while others were focussed on a single technology expansion (e.g. Gary and Larsen [41], and Ford [42]). Moreover, as GCE models consider perfect market conditions (i.e. where a quick recovery of profits is paramount), only mature technologies were considered. Within these generation technologies, fossil-fuel technologies were preferred mostly. The only exception for the choice of technologies can be seen in the models by Hasani-Marzooni and Hosseini [39] and Qudrat-Ullah [40]. The former included wind power whereas the latter used aggregated renewable technologies alongside nuclear power.

The generic causal structure used by GCE models is presented in Fig. 4. According to this structure, GCE decisions were made based on the profitability assessment of a particular investment. There was a delay between the investment decision being made and the actual generation capacity coming into operation. The supply-demand gap along with technology capital cost and market price of electricity were the crucial factors to be considered for the return on investment.

Though the general structure presented in Fig. 4 is at the core of GCE models, each study tailored it to suit its own focus. Gary and Larsen [41] disregarded capacity retirements which could send a flawed signal of total capacity to decision makers, thus undermined the effectiveness of the model's behavioural approach in decision making. Likewise, Olsina et al. [38] incorporated variable efficiencies over the operational life of technologies for electricity generation. Other studies chose to consider a fixed efficiency value.

The price estimation of electricity by Olsina et al. [38] was modelled by the interaction of demand and supply curves while the one developed by Ford [42] relied on average price of electricity. Furthermore, Olsina et al. [38] considered the demand to be price inelastic. This was a weak presumption as it neglected long-run changes in demand which may result due to adopting energy efficiency measure. This drawback was improved by Hasani-Marzooni and Hosseini [39] in their model by considering the demand to be elastic. In the same context of price of electricity, Hasani-Marzooni and Hosseini [39] used the total electricity generation to influence the price of electricity instead of using the supply demand gap of the system. Though it served the purpose, it made the model to be less strategic and more operationally inclined-a contradiction to the focus of GCE models.

It was also found that each of the GCE model was focusing on a particular national market. For example, Gary and Larsen [41] focussed on the UK, Ford [42] modelled the USA market, Olsina et al. [38] developed a GCE model for Argentina, Qudrat-Ullah [40] for Canada, and Park et al. [43] for Korea, to name a few. This trend seemed to be very logical as each country's market has some distinctive characteristics. Despite the geographical difference, all models reported a similar result. Simulations showed a cyclic behaviour in the total operational capacity and the price of electricity. This output was endorsed to power plant construction delays, and cognitive limitation of investors' ability to foresee the market trend.

Generation capacity expansion issue also deals with a topic of capacity payment mechanism. This mechanism serves as an incentive for expanding generation capacity. The objective of this payment, from regulator to generator, is to ensure a certain capacity above peak demand to hedge any risk of supply deficit. Description of various capacity mechanisms can be found in [44]. The main variable to define a capacity payment mechanism was supply-demand gap; the larger the gap, the higher is the payment from regulator to investor. To identify the level of capacity payment, various approaches were being used. These include probabilistic approach adopted by Park et al., [43] and Arango [45], a market oriented one by Assili et al. [46], and finally a hybrid of fixed and market oriented one by Hasani and Hosseini [44]. Table 5 summarizes the studies and the approaches used.

Park et al. [43] modelled the capacity payment mechanism based on identifying loss of load probability (LOLP) calculations. Eq. (2) and Eq. (3) show the relationships.

$$\text{LOLP} = f\,(demand,\ installed\ capacity) \tag{2}$$

$$\text{LOLP}\ based\ capacity\ payment = \text{LOLP} * (Value\ of\ Loss\ of\ Load{-}Marginal\ Price) \tag{3}$$

The study assumed a fixed Value of Loss Load to be flawed. There were two different classes of generators in a system; ones that supply a base load and those supplying the peak load. Value of Loss of Load for peak generators was much higher than for the base load suppliers. Arango [45], on the other hand proposed deterministic market oriented approach for capacity payment. The model relied on interactions between price, demand, economic dispatch, bidding price, installed capacity, and investment decisions fashion. However, there was lack of mathematical formulations for the proposed model specifically in a feedback setup.

Assili et al. [46] in their study used a probabilistic approach to calculate LOLP. However, instead of using an exponential decay for LOLP calculation as used by Park et al. [43], a binomial distribution function was used in the model. Hasani and Hosseini [44] used a hybrid of fixed and variable capacity payment mechanism. Fixed payment values were set in accordance to the supply-demand gap while the variable part was made contingent upon the extra generation capacity anticipated.

Table 5
Capacity payment mechanism result comparison.

Capacity payment mechanism	Prime decision variable	Reference
Probabilistic-fixed	Supply–demand gap	Park et al. [43]
Fixed-variable hybrid	Supply–demand gap	Hasani and Hosseini [44]
Market oriented variable	Supply–demand gap	Arango [45]
Probabilistic-variable	Supply–demand gap	Assili et al. [46]

GCE models with capacity payment mechanism showed that the cycles or oscillations seen in GCE problem were reduced irrespective of the type of capacity payment mechanism employed. Furthermore, it seemed that variable capacity payments were better than fixed payment mechanisms.

Models reviewed in this category explained that it was difficult to balance supply and demand in electricity sector. It was found that investor needed a continuous financial support in order to ensure safety margin of capacity. At present, it seemed that fossil fuel technologies were the preferred over renewable technologies in GCE models. Finally, planning and construction delays in the expansion of generation capacity were critical to be considered.

4.3. Financial instrument models

Financial instruments category comprises of studies that modelled various mechanisms to promote investments in renewable generation capacity. The need for such instruments was due to high cost of renewable technology [47], and to be able to shift electricity generation on a more sustainable track [48]. These instruments comprised of two quite similar entities, namely, Tradable Green Certificates (TGC) [49,50] and Zero-Emission Certificate (ZEC) [51], along with the FiT scheme [35], and a general investment incentive scheme by Alishahi et al. [52]. Table 6 summarizes the core structure used by various models in this category followed by a comprehensive discussion.

The financial instrument of TGC by Ford et al. [49] and ZEC by Kunsch et al. [51] relied on a generic supply and demand structure for the certificates. Both generators and distributors can trade these certificates in the market. It was assumed that the investors will be able to generate extra income to expand their renewable generation capacity by trading these certificates. Kunsch et al. [51] modelled the ZEC market more comprehensively as compared to the TGC market by Ford et al. [49]. Six technologies for electricity generation were considered, five being fossil-fuel based, and wind power from renewable side were modelled for ZEC, while only wind was chosen for TGC market. The simulations showed that by trading ZEC, both generation and distribution companies would be able to reduce their cost of operation, increase their renewable technology capacity along with reducing emissions. In contrast to Ford et al. [49], ZEC model considered power plant decommissioning which was a realistic way to model generation sector. However, Kunsch et al. [51] considered substitution between fossil and wind power based on the high price of ZEC was misleading. This consideration was a misrepresentation because there is a long lead-time from making a decision to invest in a new technology and actual operation of technology, during which the market conditions may change.

Seeing the drawback of substitution between fossil and renewable technologies in context of TGC, Ford et al. [49] and Hasani-Marzooni and Hosseini [50] focussed on just one renewable technology, namely, wind power. Unlike Ford et al. [49], the

Table 6
Financial instrument model core structure and weaknesses.

Financial Instrument	Reference	Core model structure	Technology	Weakness
TGC	Ford et al. [49]	Supply and demand of certificates	Wind	Wind capacity retirements were ignored making certificates prices to reach to stable level quickly
ZEC	Kunsch et al. [51]	Supply and demand certificates	Wind	Only one renewable power technology modelled. The intermittency of renewable was disregarded.
TGC	Hasani-Marzooni and Hosseini [50]	Expected profitability of investment	Wind	No mention of how wind power will supply base load only.
Feed-in Tariff	Hsu [35]	Expected profitability of investment	Solar PV	Capacity retirements as well as permitting and construction delays were ignored.
General incentive	Alishahi et al. [52]	Expected profitability of investment	Wind	No mechanism presented can match the timing of wind power and peak demand

price of electricity and the TGC were both modelled by Hasani-Marzooni and Hosseini [50]. Furthermore, the issue of intermittency of wind power that was disregarded by Ford et al. [49] in their model was tackled by considering a variable capacity factor for the technology by Hasani-Marzooni and Hosseini [50].

Both these simulation studies on TGC showed that TGCs attained high prices when there was a gap between the operating capacity and the targeted wind capacity. However, when the capacity target is achieved, the price of certificates plummeted. This rise and fall of TGC prices resulted in wind capacity oscillations. TGC price oscillations were attributed to decision-makers imperfect foresight of future, and project construction delays. This situation gave an important insight that there is a limit to certificates market. Hence, the support mechanism needs to be restructured for continuance.

Similarly, Alishahi et al. [52] evaluated various financial incentive settings for promoting wind power capacity. These settings include fixed incentive, and a market based incentive. The authors used probabilistic wind resource availability in contrast to Ford et al. [49] and Hasani-Marzooni and Hosseini [50]. The model relied on expected profitability of investment for decision making. The expected profitability is given in Eq. (4).

$$Expected\ profitability = f\,(fixed\ incentive,\ market-based\ incentive,\ investment\ cost) \tag{4}$$

Fixed incentive, a portion of investment cost, was taken exogenous to the system while market-based incentive depended upon the market price of electricity. Simulations showed that fixed incentives resulted in higher wind capacity as compared to market-based ones. Authors recommended on the basis of their analysis that the electricity should be supplied to the consumers only when electricity price is high. Unless there is a physical mechanism to store wind power, the recommendation seems less practical.

Finally, in this category, Hsu [35] developed a model to evaluate the FiT scheme in promoting solar photovoltaic (PV) investments in Taiwan. FiT is an advanced form of fixed incentives [52]. The model performed the cost-benefit analysis of FiT and subsidies under various scenarios. Simulation showed that by increasing FiT rate, solar PV investments increased exponentially. Like Ford et al. [49], Hsu [35] also did not consider solar PV capacity retirements. Considering capacity retirements as well as permission and construction delays can substantially surface different dynamics, rather than exponential rise in PV capacity. Beside this, the effect of electricity demand on solar PV investments was also ignored. This linkage is crucial as it shows how much renewable technologies are able to sustain demand.

The SD model developed in this category seemed inclined to discuss financial barriers to renewable power technology. Other barrier to promotion like technical, institutional, public acceptance and awareness [53] were largely ignored. As for the choices of technology to be modelled, wind power was given preference over other renewable technologies, except solar PV.

4.4. *Mixing-methods models*

Mixing methods of modelling techniques enriches the analysis of a study. In the same context, SD has been mixed with other modelling methods. These studies were evaluated in this subsection. Model structure and results were excluded from the discussion as they were not in scope of this category.

The first of mixing method studies was reported by Dimitrovski et al. [54]. The authors combined engineering optimisation and causal feedback approach of SD. The hybrid model used western electricity market of USA as a case. The hourly wholesale electricity prices were modelled in MATLAB/Simulink routines. These routines were then called in the SD model built in VENSIM® software. The study results showed the likelihood of synergy between shorter time resolution engineering approach and longer time resolution approach of SD models.

Periera and Saraiva [55] reported a novel approach of combining SD with an artificial intelligence technique of genetic algorithm (GA). Like Dimitrovski et al. [54], the model attempted for optimization. SD model provided information on long-term price and demand dynamics of electricity, along with share of various capacities for power generation. This information was used to devise optimised expansion plans using GA. The GA was implemented in MATLAB whereas SD model was implemented in POWERSIM®. The interface between the two software packages was provided by Microsoft EXCEL. The study highlighted that the descriptive nature of SD can effectively be transformed into a prescriptive optimization one.

SD and decision tree approach were combined by Tan et al. [56]. The proposed methodology tested wind power investment decision by a hypothetical firm. The cash flow data generated by simulation model was subjected to a decision tree. Unlike Dimitrovski et al. [54] and Periera and Saraiva [55], no interface was mentioned to have been developed between SD and decision tree model. However, the study successfully showed flexibility of SD model's output being channelized into sequential characteristic of a decision tree.

Finally, Zhao et al.'s [31] model employed SD and Agent-based modelling (ABM) approach. The study was divided in two levels: lower and upper. At the lower level, payback period for solar power investments was calculated while at higher level, a general adoption process was evaluated. At both levels, SD and ABM were applied. This setting proved advantageous as it gave flexibility in bringing extra details, in this case, hourly distribution of electricity load; providing enriched results.

The mixing methods category showed the compatibility of SD with other modelling methods. It can be inferred that the motivation of combining SD with other techniques was to compress substantial amount of information into a specific decision action. However, there is lack of literature in electricity sector modelling that combines SD model with a multi-criteria approach, and extending a static approach to a dynamic one.

4.5. *Demand-side management models*

This category includes models that focus on the demand-side management (DSM) of electricity supply chain. DSM covers all those policies or actions that intended to reduce electricity consumption, either by substitution of higher efficiency end-use technology, or altering the time of use of energy [57].

Substitution of higher efficiency devices was modelled by Dyner and Franco [58] and Ben Maalla and Kunsch [59]. The former study used SD approach to model fluorescent lamps adoption while the latter tried to highlight the adoption of domestic combine heat-power (μ-CHP) technology. Dyner and Franco [58] relied on the price of technology as the main variable to choose between incandescent and fluorescent lamp technologies. According to this structure, if the number of fluorescent lamp user increased then the number of incandescent lamp user decreased. This reduction further enhanced the fluorescent lamp users' adoption rate. On the other hand, Ben Maalla and Kunsch [59] employed a well-structured Bass model of technology diffusion. μ-CHP diffusion model showed an S-shaped growth curve; typical for the adoption of new technology.

Finally, Elias [37] developed a model for identifying ways to curtail escalating electricity demand in New Zealand's residential sector. Unlike Dyner and Franco [58] and Ben Maalla and Kunsch [59], a focus group approach was used to develop the casual loop diagram for the problem. This approach proved to be more comprehensive as compared to one followed by Ochoa [28] for developing a qualitative model. The iterative process resulted in a unanimously agreed model. Analysis of model revealed that public behavioural changed to use of electricity as the most effective mode to reduce demand. This finding is in contrast to previous studies in DSM which proposed substitution by more efficient appliances.

There was a limited SD literature on DSM. The reason for this scarcity could be power generation, due to its association with security of supply, takes priority over efforts to curtail demand.

4.6. Micro-world models

Micro-worlds provide laboratory setting where users can conduct experiments, improve their proficiency in decision-making, and learn about dynamic complexity of a problem. In the electricity sector, so far only two studies have reported the use of a micro-world;. i.e. Dyner et al. [60] and Paşaoğlu [61].

Dyner et al. [60] named the micro-world as EnerBiz. The micro-world focused on the Colombian electricity market. The micro-world facilitated trading and risk management capabilities of market participants. The second micro-world, developed by Paşaoğlu [61], named Liberalised Electricity Market Micro-world (LEMM) was indented for an academic environment for Turkey. EnerBiz and LEMM were tested by real users in their respective countries, but the outcome of the exercise was the same. Each group of users valued respective micro-worlds for increasing their understanding of the feedbacks, delays and dynamics in the electricity sector. Both these micro-worlds focused on the generation side only which facilitate decision making but they lacked in assessing technologies for generation especially the renewable ones.

5. Conclusions

In this paper, an effort has been made to highlight the contribution of SD modelling of electricity sector. The review revealed that policy assessment and generation capacity expansion were the two most modelled issues. Policy assessment models were developed at national level to gain insight on effect of new policies. These policies include encouraging private sector investments, nuclear phase out or deregulation of sector. Generation capacity expansion addressed the reliability and affordability of generation system. Simulations highlighted the dependence and interaction of investment decisions on profitability calculations. A market based capacity payment was found to ensure timing generation expansions yet this mechanism was unable to eliminate investment cycles. Models in financial instruments category were concerned with boosting renewable technologies for electricity generation in a competitive market. In mixing methods category, flexibility of SD with other tools and techniques was confirmed. In demand side management category, it was found that information dissemination regarding rational use of energy is crucial for influencing demand. Finally, in the micro-worlds category the importance of learning and experimenting in electricity markets was asserted. Due to the commercial value, not many articles reported on micro-worlds. Furthermore, the review revealed that there is a generic supply-demand structure underlying all models. The changing market conditions and regulations, which disturb the supply-demand equilibrium, were the prime motive of using SD approach.

From the review future direction for researchers using SD can be suggested in the energy sector. These include developing models focusing on phase-out of fossil fuel technology in general, and nuclear technology in particular. On capacity expansion side, transmission and distribution networks factors could be included. This inclusion would bring richness to the model. Likewise, it is suggested to have more hybridization of SD and artificial intelligence techniques. Finally, side management public's attitude towards time-of-use could be modelled.

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Review of System Dynamics models for electricity market simulations

by Felix Teufel, Michael Miller, Massimo Genoese and Wolf Fichtner

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Review of System Dynamics models for electricity market simulations

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Abstract

This paper provides a review on modeling electricity markets with System Dynamics (SD) focusing on deregulated electricity market models. First the SD method is classified within the wide field of electricity market modeling. Then all distinctive properties of the SD method in this context are elaborated. After an overview of first SD models in energy economics, a comprehensive review of models of deregulated electricity markets is presented. The review captures more than 80 publications in the field of SD energy market modeling. Some tendencies could be identified: Firstly SD models are more and more combined with other methods like generic algorithms, experimental economics or analytical hierarchy processes. Secondly, stochastic variables are considered increasingly. Thirdly, models show a higher level of detail and increasingly evaluate aspects such as new markets designs or new market components and their interdependencies.

Key Words

Deregulated electricity market, market model, market design, system dynamics, model review, investment decisions, regulation, market power, evaluation of strategic concepts

Highlights

- A review on System Dynamics models for electricity market simulations is provided
- More than 80 publications and models have been analyzed and are presented synoptically
- A classification of the System Dynamics methodology within electricity market modeling approaches is provided
- Synoptical table of over 80 models is presented
- Trends of modeling electricity markets with System Dynamics are identified

1. INTRODUCTION

Electricity markets are facing substantial changes globally. The deregulation of the electricity sector, increasing supply of renewable energy production as well as regulatory interventions addressing topics such as climate change, security of energy supply and affordable energy prices lead to constantly changing boundary conditions.

This requires both market actors and market designers to examine and fully understand the impact of changing certain framework conditions. As extrapolating historical data is not sufficient, electricity market models that incorporate changing conditions are needed.

Different methods for modeling are utilized and have been established. This paper focuses on System Dynamics (SD) models of the liberalized electricity market. As this study covers a very wide range of publications, like resource models, supply-demand models, generation models, the application of these models is not discussed in detail. However, this study gives a broad selection and comparison of more than 80 publications of SD electricity market models. The paper starts by outlining how to model in SD and gives a classification of SD in electricity market modeling.

The aim of this review is to comprise the status quo of SD electricity market models. The paper provides a categorization of these publications by identifying major fields of applications. Furthermore properties of the SD methodology are introduced and the modeling approach is classified within the wide field of electricity market modeling. Moreover the identification of differentiating factors of the reviewed models are identified and synoptically presented in a tabular overview. The review closes with a summary and outlook, which includes the identification of modeling trends.

2. SYSTEM DYNAMICS IN ELECTRICITY MARKET MODELING

a. CLASSIFICATION OF ELECTRICITY MARKET MODELING

Besides the System Dynamics modeling technique, several other modeling methods are applied to electricity markets. Ventosa et al., (2005) identify three main modeling categories: optimisation models, equilibrium models and simulation models. Enzensberger, (2003) distinguishes Top-Down and Bottom-Up models, where optimization and simulation models are part of the bottom-up approaches and equilibrium models part of the top-down approaches. Top-Down models have a more macroeconomic perspective and seek to model developments within the entire economy covering the most relevant sectors. Usually this broader perspective requires a higher aggregation level instead of modeling explicit technology options like single power plants. Important classes within the field of top-down models are Input-Output [I/O] models and Computable General Equilibrium Models [CGE] (Sensfuß, 2008). Bottom-Up models are also called partial models as they usually focus on the considered sectors (e.g. electricity and heat) and do not cover interactions with the entire economy. Möst & Fichtner (2009) compare optimizing models and system dynamics models. They state that optimization models try to optimize a system with given boundaries (e.g. electricity demand) finding e.g. a cost minimal solution. Simulation models in general instead try to simulate the effects of different actions. Agent-based models and system dynamics models are the two main representatives of simulation models. As stated in the previous section, SD simulate causal effects within components of a system in time. This enables to include an actor′ s perspective into the simulation, which is also a main advantage of agent-based simulation models. Whereas in agent models learning behavior of market participants can be modeled, in System Dynamics models difference equations are used to model the temporal and structural interdependencies between the elements of the models. These models generally are used to model liberalized electricity markets and particularly to model market imperfection and strategic behavior of the market participants.

b. PARTICULARITIES OF MODELING ELECTRICITY MARKETS WITH SYSTEM DYNAMICS

To create a model with SD, Forester (1961) claims, that there are basically three “databases” that provide the knowledge base. The first fundamental database is data about historical developments and presumptions on possible approaches how to solve the faced problem. Forester calls this the “mental database” , which can be described as compilation of cognitive impressions. Expectations about future system performance are also part of mental databases, however should not be considered in the model. As many systems show non-linear behavior those intuitive solutions and approaches are usually not valid as they tend to assume linearity.

“Written databases” are either transcripts of mental models from the “mental database” or approach the considered problem only partially and do therefore play a minor role in SD modeling.

Due to the important role of causalities in SD modeling, the third database, called “numerical database” , is of little importance. This is in contrast to many other methods that conduct extrapolation on basis of that information. The numerical database is an incoherent accumulation of quantitative data, which does not contribute to the description of feedback loops, a major property of representing certain causalities within SD models.

By taking this conceptual differentiation of information sources into account, a distinctive property of the SD methodology can be exemplified. Not only the final SD model but also the modeling process contributes to a better understanding of a system and relevant causalities as assumed linear system behavior is neglected and exaggerated focus on numerical data is prevented. Vogstad (2005a) describes this as follows: "Selecting the important relationships from the less important ones can only be done by trial and error, due to our cognitive incapabilities of dealing with complex nonlinear systems. Defining the adequate system boundaries of a model is therefore an iterative process. As we understand more about the problem, we are able to identify important relationships from the less important ones."

As SD simulations are quantitative models, causalities and coherences are implemented with differential equations (Botterud, 2003). This is done by the help of stock and flow variables. A simplified model is illustrated in Figure1.

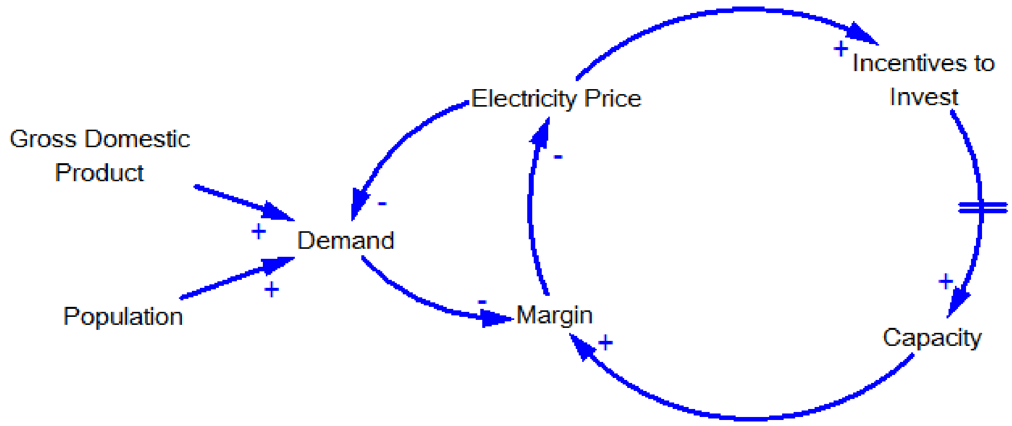

Figure 1: simplified Scheme of a dynamic electricity market modeling (according to Arango et al. (2002))

Arango et al. (2002) describe the dynamic behavior of electricity markets with a focus on the development of installed electricity production capacities. The aggregated view shows that electricity demand depends on demographic and economic development as well as on the elasticity of electricity demand. A high electricity price stimulates investments in electricity generation facilities, which lead to higher capacity and thus to higher margins. The double prime between the variables "incentive to invest" and "capacity" indicates that planning, approval and building processes delay the actual increase of capacity. Positive and negative signs stand for reinforcing or counteracting influences. Sterman (2000) states: "All dynamics arise from the interaction of just two types of feedback loops, positive (self-reinforcing) and negative (self-correcting) loops. Positive loops tend to reinforce or amplify whatever is happening in the system, while negative loops counteract and oppose change. [...] By stringing together several loops we can create a coherent story about a particular problem or issue."

Literature lists six major characteristics as differential factors comparing the SD methodology to conventional approaches of electricity market modeling.

One is the above mentioned capability to implement delays, which is very important when dealing with energy economics. Time consuming planning, approval and building processes need to be incorporated into the model.

Furthermore the consideration of bounded rationality is of particular importance. In contrast to optimization problems, where perfect information and rational agents are assumed modeling in SD gives the opportunity to implement realistic processes with immanent preoccupations, misinterpretation and wrong considered effectiveness.

Thus, decisions and its developments can be modeled descriptively, by considering bounded rationality. Hence it is possible to implement decision processes without determining normative optima, like it is done in other methods (Jäger et al., 2009).

Whereas classical optimization methods assume reliable and complete information about future development, SD allows modeling uncertainties concerning price, quality of information, future demand and expected regulatory specifications (Dyner, 2001). This principle is known as "imperfect foresight".

Most other models assume immediate convergence to market equilibrium. Yet, SD models consider that suboptimal decisions and delayed impact results only in an approximation of supply and demand (Jäger et al., 2009).

As SD modeling focuses on causal relations, further aspects such as qualitative influences are easily incorporated. Botterud (2003) writes: "Consequently, system dynamics models usually have an aggregate level of detail, while the scope of the models can reach beyond what is usually included in traditional analytical methods."

The applicability of SD models for electricity market modeling is described in detail by Pereira & Saraiva (2009). Sanchez et al. (2007) and Sanchez (2009) give a detailed review about the classification of other methods, which will be addressed in the next section.

3. METHODOLOGY AND MODEL REVIEW

The broad diversity of addressed questions, model structures, aims and range of application was collected. For this reason, the publications have been evaluated regarding background information, characteristics, fields of application, model type and further information. Based on the major research question the considered models are structured on a thematic basis as shown in Figure 2.

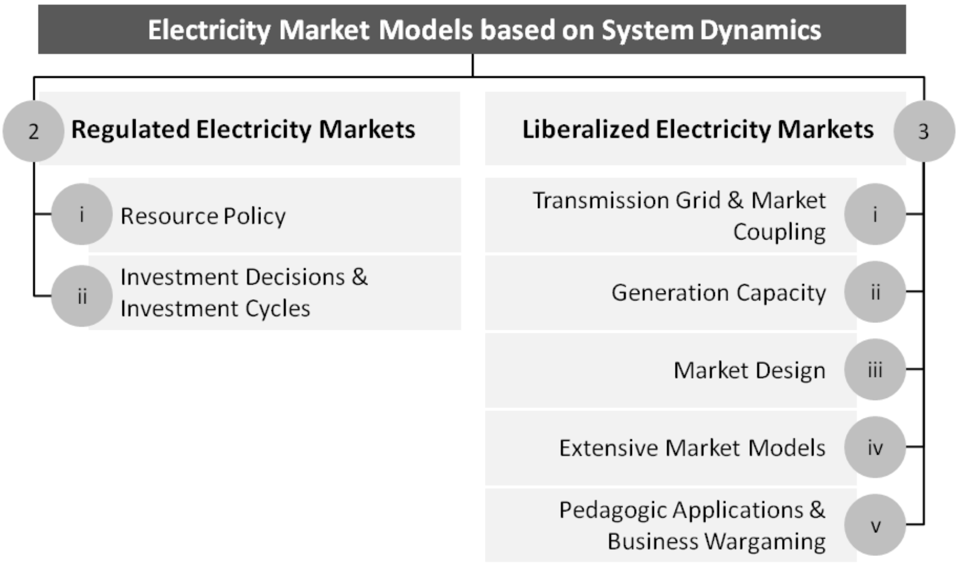

Figure 2: Major research questions as thematic structure.

In general, the models can be categorized in models which have been developed for regulated electricity markets and models for deregulated electricity markets. Former models mainly discuss dynamics of the energy system and are briefly described in the following section, as they are the basis for the further developed models for the liberalized markets. These models have been characterized into those who consider grid restrictions, addressing issues of market design, market power and extensive models. Minor roles play other models developed for pedagogic and business wargaming applications. The most important models representing also the largest subsection in this paper are the models analyzing the dynamics of investment decisions and investment cycles. The overview will be provided in the following chapter, before summarizing all results in table 1.

a. REGULATED ELECTRICITY MARKETS

i. RESOURCE POLICY

After Forester had published the principles of the SD method in 1961, models regarding energy were mainly developed to analyze the impact of resources on economic development.

Following their global scope the first models were named World. On the basis of the model World3, the well-known book "Limits to Growth" by Meadows et al. (1972) was published. Apart from the methodological provenance those models are important as these highly aggregated models are the root for policy evaluation with SD.

The advancement of the Woarl3 model, for example COAL1 and COAL2 by Naill (1972) and Naill (1976) provided the basis for the evaluation of energy policy measures in the United States for a long period. FOSSIL1, which is based on COAL2, was the first model that explicitly modeled the electricity market. Backus (2009) describes the history of extensions and advancements of those models in detail. The U.S. Department of Energy (1997) provides a synoptic review of the evolution of these models over the time as shown below.

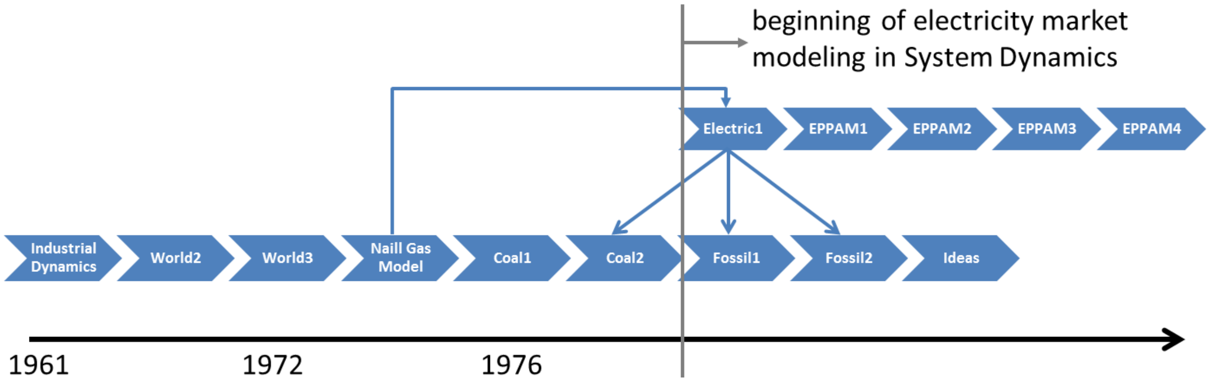

Figure 3: First SD models with increasing focus on electricity markets (according to U.S. Department of Energy (1997))

Fossil2, a second generation successor of the Coal2 model, is another eminent model that was used as starting point for further models such as "Integrated Dynamic Energy Analysis Simulation (IDEAS)" and "Feedback Rich Energy Economy (Free)".

Biair (1991) states, that Fossil2 simulates the energy demand and supply in the United States in a period of 20 to 40 years. Future demand of each energy category like light, thermal energy, steam heat and mechanical energy is modeled endogenous. The energy price is calculated in a demand feedback loop.

The U.S. Department of Energy (1993) published the model named "Integrated Dynamic Energy Analysis Simulation (IDEAS)". IDEAS is a long-term model of the U.S. energy demand and supply, which was used to analyze the dependence on oil imports. According to the U.S. Department of Energy (1993) the results were used to determine measures of energy policy.

The model "Feedback Rich Energy Economy (Free)" implemented by Fiddaman (1997) and Fiddaman (1998) examines the relationship between environment, politics, economy and society. Particularly the relation of economic development and energy demand is discussed.

The previously discussed models were quite aggregated. Dependencies between resource availability, security of supply, economic development and environment have been examined. Contrary to this broad scope electricity utility policy and planning analysis models (EPPAM) only consider the electricity supply.

Aspects such as energy efficiency, environmental policies, operational stability, production capacity expansion and the development of electricity prices are examined with the help of models of the conservation policy analysis model family (CPAM) (Ford, 1997), (Ford et al., 1987), (Neubauer et al., 1997), (Dyner et al., 1993).

Resource policy screening models (RPSM) expand CPAM models with respect to the modeled generation technologies. Combined heat and power generation and smaller generation units, mainly renewables are taken into account (Neubauer et al., 1997).

Energy2020 is derived from the models shown in Figure 3. After refining the modeling of supply and demand side for energy supply in the United States, this model addresses the need for a more regional perspective on energy policy (Backus, 2009). Besides the U.S. and Canada, this model was already used in more than 20 countries.

Apart from the above mentioned models that derived directly from the MIT model family numerous other models were developed in the field of electricity generation and supply. Their main focus is the simulation of future dynamics and impacts of political decisions.

The model Threshold21 accomplishes the social, the economical and the ecological system. It can be used for analyzing aspects such as population growth, education, energy policy and economic developments. Among others Bassi (2006, 2007, 2008), Barney et al. (1995) and Balnac et al. (2009) describe this approach.

Another model on this aggregated level combines approaches of decision theory and multi-sector input-output models with SD (Osgood, 2003). However electricity markets are not modeled explicitly in this program.

ii. INVESTMENT DECISIONS AND INVESTMENT CYCLES

Ochoa & Van Ackere (2007) examine the Swiss electricity market regarding the electric resource adequacy. The influence of the emergent liberalization and the nuclear phase out on the development of production capacity, import and export are evaluated. Results of the study lead to the conclusion that Switzerland needs a long-term binding regulatory framework for future investments.

Ochoa (2007) confirms the aforementioned findings by focusing on the import dependency of Switzerland. The simulation shows that with clear regulatory specifications the electricity price can be reduced through imports from France. Moreover, earnings can be generated through exports, mainly to Italy.

Rego (1989) describes the capacity bottleneck problem in the regulated electricity industry in Argentina. A SD model with a capacity growth control mechanism is developed to analyze the trade-off between delayed development (costs due to lost load) and accelerated expansion (financial costs). For this purpose price calculations are based on a load duration curve and a merit order dispatch. Findings of the simulations are the optimal policies in terms of minimizing the short- and long-term supply-demand gap.

A tendency towards models with an increased level of detail can be observed. Yet there are still aggregated models which are relevant for energy policy. The focus of this review however lies on models of deregulated electricity markets. Therefore the above mentioned models have to be seen as a selection of major models that form the basis of electricity market modeling with SD. The focus of this paper is on deregulated market models that are presented in the next chapter.

b. DEREGULATED ELECTRICITY MARKETS

In the following, deregulated and liberalized electricity market models implemented in SD are briefly described.

i. GENERATION CAPACITY

Arango et al. (2002) analyze the investment in power generation capacities in Colombia. "Micro world" is an interactive SD model and game. A potential investor reaches periodic decisions within a defined scenario. This enables the decision maker to assess the impact of investments in electricity generation capacity. The user is able to observe the evolution of the system regularly and reach a decision whether to do or defer an investment in power generation. In this context risk and uncertainty analysis with regards to capacity expansion is considered. Uncertainty is implemented by modeling variables stochastically. Among others electricity price, regulation, demand growth and technology development. Major decision factor is the estimated project cash flow. The model simulates investment cycles. The particular generation mix of Columbia is reflected by implementing a hydrology module. Hence restrictions of the transmission network, fuel markets, impact of possible new regulation, and influence of the load curve over dispatch are neglected.

Gaidosch (2007) focuses on the German electricity market. The model simulates a time period 30 years and tries to identify drivers for investment cycles in power plant investments. Although the model could support decision processes, the identification of drivers of investment cycles is focused. Thus the model supports the analysis of the impact of various politico-economic measures. The investigation shows, that the existing market structure of the German electricity market does not prevent from investment cycles with high price volatility.

Sanchez et al. (2008) also examine long term investment dynamics. For this purpose System Dynamics is combined with approaches from credit risk theory and game theory. The cost of taking a new loan increases with the volume of investments made. Thus higher credit costs result in a decreasing discounted present value of a project. Transmission restrictions are not considered. The model is generic and not calibrated to a specific market.

Kadoya et al. (2005) evaluate to which extent deregulation is the cause of cyclical investment behavior. The model is calibrated to the two electricity markets Pennsylvania-New Jersey-Maryland Interconnection (PJM) and Independent System Operator-New England (ISO-NE). The simulation results lead to the conclusion that deregulation causes cyclic investment behavior. Special feature of the model is a detailed profitability assessments used by companies for investment decisions. Prices therein are captured with price forward curves.

Ford (2001) examines a model based on fundamentals, which Gaidosch (2007) formulated in his outlook. The model is based on Ford (1999). In total five different scenarios are studied concerning investors behaviors. The scenarios differ in the knowledge about power plants under construction and the consideration of these. Results of all scenarios are that there is a cyclical investment behavior in power plant construction.

Syed Jalal & Bodger (2010) try to discover future dynamics with respect to cyclical investment behavior for New Zealand’ s electricity market. The most important feedback loops are the permission and the construction loop, the interactive loop that combines investments and market as well as the actual investment decision loop. Contrary to a study by the New Zealand Electricity Commission, the authors detect a risk of cyclical investment behavior.

Pereira & Saraiva (2009, 2010, 2011) present an approach that combines a genetic algorithm and SD. Their aim is to provide decision makers the opportunity to simulate decisions based on the model. The generic algorithm is used to maximize the profits of each participant. With help of the SD model the long term electricity demand and electricity price development is simulated. Decisions are supported by simulation projections for the specific point in time. The model can be used by enterprises to create risk reduced and robust expansion plans and by regulatory authorities to gain a better understanding of market developments.

Olsina et al. (2006) describe the mathematical background of cyclical investment mechanisms in detail. The model is suitable for enterprises and regulatory authorities to create complex scenarios and gain insights affecting investment decisions. “Imperfect foresight” and delayed disposability of power plant investments are taken into account. The study shows that by choosing the optimal generation technology mix, variable and fixed costs are covered. Therefore preferably the competition between different technologies is simulated as an alternative to competing market participants.

Bunn et al. (1993) point out characteristic SD properties in contrast to classical optimization methods of operations research. They develop a long-term planning model considering increased expected return on invests, changes in taxation frameworks and conditions for acquisition of capital. An optimization and a SD model are used. Major component of the model is the feedback loop of capacity payments for utilities, which is orientated at the loss of load probability per half-hour. The aspects of market structure, risk and strategic competition is main focus of the analysis. The study claims that the price is an insufficient reliable indicator of future needs of power plants. Therefore utilities act risk averse and invest in more flexible technologies like gas. In addition, market shares are shifted due to different credit terms of competitors and the increased risk leads to higher consumer prices.

Larsen & Bunn (1999) summarize the above mentioned aspects and address the challenges resulting of the transition from a monopolistic to a competitive market. The authors examine with the help of the above described model, if investment behavior is changed by the transition from a monopolistic to a polypolistic market.

Gary & Larsen (2000) compare SD models with equilibrium models with regard to the approach of reaching supply-demand equilibrium. Using causal diagrams, it is illustrated that equilibrium models assume immediate equilibrium whereas SD models often doesn’t achieve this state at all due to time delays and feedback loops. Focus of the investigation is the development of power plant capacity under consideration of dependencies between the gas and the electricity market. The electricity marked is assumed to be designed as a pool, such that the pool price increases in case the reserve margin decreases. This provides a signal to invest in new capacity.

Acevedo & Aramburo (2009) implement their model with the aim of providing decision support. They are using approaches of experimental economics combined with an electricity market model in SD to study cyclical investments. Two different model variants are implemented. Whereas in the first variant producers always offer their full capacity of generation units the second variant requires the user to decide on the share of actually offered capacity on the market. The only restriction is that the user offers at least 70 % of the installed capacity. Major result of the simulation of 12 simulated experimental markets is that the requirement for full capacity bidding leads to cyclical investment behavior whereas the ability to decide on the actual offered capacity leads to weaker indications of cyclical tendencies. In those simulations a tendency towards Cournot Nash prices was observed. These results indicate that varying capacity utilization allows having higher prices.

Sanchez et al. (2007) focus on another element of deregulated electricity markets. The model considerers oligopolistic market structures and vary credit terms depending on the company situation. A conjectured-price-response mechanism considers that bidders are not only price takers but even influence the price with their bidding behavior. Sellers estimate their influence on the expected price and chose the best combination of quantity supplied and price accepted. The market equilibrium with the provided quantity and the associated price is then calculated. The oligopolistic structure of electricity markets is captured by a preferential treatment of larger enterprises with respect to credit terms.

Tan et al. (2010) model the process of analyzing investment alternatives using the example of wind turbines. In this context, SD is combined with decision trees. This combination allows incorporating the consideration of the complexity of such processes with SD and the flexibility of the management by applying the decision tree method. Results of the simulation runs are cash-flows of the projected periods. The resulting decision tree is solved by backward induction.

Vogstad et al. (2002) model the Nordic electricity market and depict short term against long term impacts of energy policy guidelines. The model simulates the electricity price, demand development, technological progress and resource availability in a 30 year timeframe. Investment decisions regarding generation capacities result from mechanisms that are defined ex ante. Generation technologies are either conventional (nuclear, coal, natural gas, natural gas with CO2 sequestration, natural gas peak load) or renewable (hydro, bio, wind onshore, wind offshore). Price elasticity and the evolution of demand are implemented exogenously. With the help of the hourly resolution technical restrictions like load gradients, start up or shut down costs are considered.

Jäger et al. (2009) develop Zertsim based on (Vogstad, 2005a) and calibrate their model on the German electricity market. The outputs of Zertsim are electricity prices, the development of generation capacities (investment decisions) and CO_2 emissions. Jäger et al. propose this model as starting point for discussions about the future of electricity markets.

Qudrat-Ullah & Davidsen (2001) examine the Pakistani electricity market. In spite of the geographical potentials for hydroelectric power generation, mostly carbon, gas and fuel based electricity generation capacities are in place. The simulation assesses how the continuation of existing energy policy guidelines would affect the future generation portfolio. The assessment is carried out with respect to three criteria: the electricity supply, the resource import dependency and the evolution of CO2 emissions. The yearly calculated demand is induced by the GDP and the electricity intensity of the economy. The latter is dependent on the average price of electricity and takes changes in electricity generating capital into account. The study concludes that the generation portfolio would significantly change towards more gas power plants with the underlying assumptions. Yet water power would decrease its share of total electricity production.

In MDESRAP, Qudrat-Ullah (2005) examines the link between electricity supply, resources and pollution. It is analyzed how investment incentives affect the generation mix and resulting emissions. Production, resources, costs and pricing, environment, capital, investment decisions and electricity demand are modeled modularly. Generation technologies are offered at the market with full costs. Qudrat-Ullah points out the suitability of the model for political decision-making processes to identify appropriate policy guidelines and measures.

Bunn & Larsen (1992, 1994) analyze investment cycles in electricity generating capacity. Drivers of the cyclic behavior are identified for the deregulated British electricity market. Particularly the stability of the system under influence of regulatory authorities is focus. Capacity payment as correcting variable is at the regulator' s command. The research explores, if investors can deduce investment decisions from the capacity payment. Their gist states that instruments like statutory publication of future investment plans lead to a more stable system.

To investigate the consequences of different regulatory measures, Ford (1983) uses a very abstract and simplified model with just two feedback loops for demand development and capacity expansion. The model explores the impact of shorter planning and permission periods on the cyclical investment behavior. Furthermore the model examines the consequences of a resource shortage. The quantitative results of the simulation might be used for decision support and political discussions.

Ford (1999) evaluates the reasons for cyclical investments in electricity generation units. The impact of several aspects, such as capacity payment, investor' s behavior and the linkage of the electricity and gas market is closely analyzed. Ford (1999) states, that the introduction of a constant capacity payment reduces the cyclical investment behavior. In comparison to business clients, private clients only seem to be affected slightly by the introduction of capacity payments. For business clients, prices rise in the short term, but decrease after a certain time, so the concept would not be disadvantageous either.

Dyner (1997) introduces a SD model to evaluate different political or regulatory incentives in the Columbian electricity market. The model is structured in socio economic influence, price formation and electricity demand and supply. Different political scenarios are simulated.

Considering CO2 taxes, capacity payments and wind power subsidies, Sanchez et al. (2007) examine the capacity expansion of electricity generation units. The model includes a strategic production cost component, a future market and a component that evaluates the credit ranking of the simulated companies. The combination of volatile feed-in (mainly renewable) and controllable generation units is examined in particular. The demand-supply balance is determined by the annual calculation of a price duration curve. Investment decisions for new wind turbines or combined cycle power plants are based on the calculation of a discounted present value of each project.

Hasani & Hosseini (2011) evaluate seven different mechanisms to ensure adequate generation capacity available. Whereas certain markets were modeled without specific market mechanisms, others introduce a price ceiling, a price floor and capacity markets. Result of the investigation is that in a capacity market the monthly update of the price signal leads to weakened cyclical investment behavior. Furthermore, Hasani & Hosseini (2011) state that a hybrid version combining a capacity market with a cost-based mechanism is most effective.

He et al. (2008) examine different regulatory instruments with the aim of avoidance of cyclical investment behavior in the liberalized market. Five scenarios are evaluated, in which the interaction of different market players and different generation technologies are not considered. In yearly simulation sequences the hourly electricity prices are calculated and integrated into a price duration curve. He et al. conclude, that under perfect market conditions, the energy-only mechanism is able to achieve the optimal level of generation investment and leads to stable and reliable market conditions. However, as real markets are not perfect, the energy only mechanism is likely to fail. Capacity payment mechanisms might help to overcome investment barriers, but could also induce over-investments problems.

Assili et al. (2008) evaluate different capacity payment mechanisms. A perfect market is assumed, where capacities are offered at marginal costs. Under these conditions, Assili et al. (2008) reason, that for long term consideration the simulation of competing technologies is more appropriate, than modeling different market players. The result of the SD-model is that a variable capacity payment leads to a stabilized marked dynamic. Fixed capacity payments also weaken investment cycles. However without capacity payments significant investment cycles could be observed.

Dyner et al. (2007) examine the Columbian market with the aim to identify if the reliability charge mechanism serves its purpose. A particularity of the Columbian market is the high share of hydropower with about 70 %. In this model, the regulation authority procures an ex ante defined quantity of pull options for electricity supply. Suppliers obtain an option premium regardless if appointed power is requested. In bottleneck situations with high prices, the regulation authority can request agreed quantities for a defined strike price. The study' s result is that a reliability charge serves its purpose in principle. However the considered instrument' s impact takes effect after a certain time, so that minor bottleneck situations may occur.

Dyner et al. (2001) analyze different regulatory requirements: role of a reserve market and an options market. The model' s result is that both approaches lead to stable markets.

Arango (2007) examines the consequences of different regulatory approaches for investments in new generation units. Beside an options market, safeguarding against failure is simulated. Utilities gain acceptance of bid, if their price is below the intersection of supply bidding and demand curve. For capacity expansion four technologies are available. Transmission grid restrictions are considered with the help of geographical distribution of generation units. Possible investments are evaluated with the real options approach. Aspects like reliability, generation costs and volatility are considered.

Park et al. (2007) evaluate different methods for rating capacity payments. For this purpose Park et al. compare a system with fix capacity payments with a mechanism where the capacity premium is based on loss of load probability (LOLP) as function of reserve margin. The model is made up of the modules pricing, capacity development and investment decision. Different scenarios are compared with a basis scenario, in which electricity prices are determined by base load marginal price and system marginal price. Beside those revenues, utilities receive capacity payments for repressed capacity. Yearly investment decisions are reached with the help of discounted present value.

ii. MARKET DESIGN

Ford (2006) analyzes the consequences of an introduction of a taxation of CO2 emissions and a fixing of CO2 emission allowance. With the model of Ford (2008) different scenarios are compared with the macroeconomic forecast of the Energy Information Administration California. Both scenarios conclude that rising electricity supply costs come along with CO2 emission reduction in the same percentile amount. Ford (2006) states, that both instruments are expedient.

Vogstad (2005b) evaluates the influence of emissions trading on the electricity market. Different trading strategies for renewable energy certificates are identified by experiments considering borrowing and banking. On the basis of historical prices, future prices are anticipated daily. As the setup is experimental, strategic aspects, like focusing on trends or consciously retention of certificates are covered.

Based on the same model, Ford et al. (2007) evaluate situations with strong wind feed-in, extensive banking and borrowing of green certificates as well as a combination of renewable energy certificates and CO2-emission capping.

Using a SD model, García-Álvarez et al. (2005) study the bidding behavior of the Spanish electricity market players regarding market power. The result is that the major utilities in Spain can perform market power. The authors, however, only describe their results and do not describe in detail the underlying model.

Although gas and electricity utilities are active on both fields, the regulation of gas and electricity markets is sometimes done by different authorities. Bunn et al. (1997) discuss the topic of market power, which is achieved by simultaneous activities in the field of gas and electricity supply. The model is described in detail by (Bunn & Larsen, 1992, 1994). Three trading strategies, namely increased volatility, retention of capacity and new hedging contracts are considered. The result of the Investigations is that in the considered market of the UK market power persists.

iii. TRANSMISSION GRID AND MARKET COUPLING

Ojeda & Garces (2007a, 2007b) evaluate the effects of a market coupling. The pooling is evaluated by seven scenarios, like nuclear power face out or increased wind power generation. Ojeda & Garcés (2007a, 2007b) conclude, that the reliability of electricity supply is improved by a jointly arrangement of the reserve power market. This occurs even though the modeled system operator maximizes its profits.

Ojeda et al. (2009) model a market based transmission network connection of two markets. The grid operators are interested in new grid capacities, if he can profit from price spreads and the right of use can be sold for an attractive price. Two regulatory approaches are evaluated, namely the retention of transmission capacity and generation capacity. By virtue of the simulation results Ojeda et al. (2009) recommend the permission of strategic behavior of transmission network operators.

Dyner et al. (2011) discuss the question, how many electricity markets can be merged by market coupling mechanisms. Several political directives are discussed. The result of the simulation is, that the market integration leads to a diminution of electricity prices and to a more efficient electricity production, related to CO2 emissions whereat technical, political and regulatory issues may not be neglected. Dimitrovski et al. (2004, 2007a) deal with the previous question how transmission grids can be modeled best possible.

Turk & Weijnen (2002) model a generic SD model for infrastructure markets. In retro perspective on the crisis of the Californian electricity market, the authors examine the causal relationship and criteria of the reliability of an infrastructural system. Conclusion of the study is that only through continuous monitoring of the identified performance criteria and appropriate measures based on this monitoring allows ensuring stability in grid operation in the long term.

Hui (2009) models in detail the problem of investment in grid infrastructure. Different incentive systems are evaluated and an improved planning process is developed.

Dimitrovski et al. (2007b) combine in their model of the Western Electric Coordination Council (WECC) short- and long-term mechanisms. Topics like regulation, investor behavior, environmental impacts and system design are addressed. A special feature is that transmission grid constraints are considered. Although the model is applied for the West African Electricity Pool, it can be applied for different countries.

iv. EXTENSIVE MARKET MODELS

While most of the modeling approaches for deregulated electricity markets do not consider competition inherent uncertainties, most of the regulated market models don' t take into account competitive dynamics and decentralized decisions. Therefore Botterud (2003) picks up this requirement and creates a model that can be used both by companies for decision support in their investment decisions in generation units as well as by regulatory authorities to simulate the market with different regulatory frameworks. Finally approaches to identify optimal investment alternatives and economic approaches for decentralized energy systems are combined. In contrast to most of the SD models in the electricity sector, Botterud (2003) determines uncertainties with a real options approach, instead of the discounted present value. The most important aspects of the model are summarized by Botterud et al. (2002).

With its SD model, Olsina (2005) addresses issues within a long-term horizon. The model examines the contribution of different market mechanism to long-term security of supply. The timing of decisions for new capacities is studied and the role of other variables that determine long-term development is considered. This also involves the question how cyclical investment behavior comes into existence. The simulation results show, that regulatory influence has to be initiated quite early, so that the necessary capacity is always available and electricity prices stay stable. The reason therefore is mainly the long delay periods. As major determinants Olsina (2005) identifies development of demand, interest rates, market concentration and price caps. Olsina (2005) argues that regulatory price caps can be used thoughtful to provide price stability.

Sanchez (2009) pursues the objective to abolish shortcomings of the SD method by integrating other simulation methods. Furthermore an important development is that Sanchez (2009) takes the oligopolistic structure of electricity markets into account. By the improved modeling of the spot and the forward market, the bidder behavior, the forecast of future prices and generation capacity models are closer to reality than before. The implementation of these aspects is described in (Sanchez, 2009). The specific application of this model is described in (Sanchez et al., 2007, 2008).

Vogstad (2004) models with "Kraftsim" the "Nord Pool" electricity market in an extensive manner. In particular, the competition between generation technologies is discussed while the competition between companies is considered secondary. Because price and demand development is modeled endogenous analysis of energy political and regulatory framework is feasible. Focus of Vogstad' s study is the supply side of the electricity market and its emissions of CO2. Even a green certificate module is integrated. Result of the examination is that in the short term more renewable generation units will be built. However, the aggregate CO2 emissions rise in the long term, because of replacement power stations of the renewable units. The green certificate module is used for developing trading strategies for market participants and for predicting the price development of the certificates. Another component of the model is the modeling of hydro power plants and hydro power storage. By quantifying the value of the stored water, generation strategies can be developed.

A peculiarity of the model of Grobbel (1999) is that grid restrictions are considered. The model is characterized by a high resolution with numerous technical details of the German electricity market. Nearly 5000 feedback loops are modeled. By considering the grid constraints, also regional differences are taken into account and are integrated into the model.

With the model LEMM (Liberalized Electricity Market Microworld) of Pasaoglu (2006) different business strategies for utilities can be evaluated as well as programs for regulatory authorities. The short and long-term dynamics of supply and demand sides are considered. Pasaoglu (2006) quotes "Excellent tool to be used in understanding, investigating and experimenting on a decentralized electricity market, especially in regard to investor behavior, supply, demand and price fluctuation, short and long term effects of various decisions and resource limitations." Decisions are taken by using an analytical hierarchy process. The model is made up of a demand, capacity expansion, electricity generation, accounting and finance module. For new investments in generation units, utilities can choose out of different technologies like solar, wind, carbon, gas, oil and hydropower. Beside political and socio-economic aspects factors like resource availability, environmental impact and costs are considered. Pasaoglu & Or (2006) apply the model LEMM and simulate several scenarios. They emphasize, that in a deregulated environment "imperfect foresight" prevails.

v. PEDAGOGIC APPLICATIONS AND BUSINESS WARGAMING

Franco et al. (2000) implemented the model EnerBiz II, for training Columbian energy and electricity traders. Franco et al. (2001) build on the existing model and permit imparting of knowledge in strategy development and risk management. Dyner et al. (2009) focus on the precise training cycle and user interface of the software. Pasaoglu (2011) describes the educational benefits of using a SD model like Pasaoglu (2006) and Pasaoglu & Or (2008) for explaining causal relationships in an electricity market. Vlahos (1998) explains in his publication the model set up of "the electricity markets micro world" and which actors play a crucial role and how the software can be used for educational purposes. Dyner et al. (2003) describe in detail how SD models can be used for training purposes in the environment of deregulated electricity markets.

Ochoa et al. (2002) examine the concept of portfolio strategy with regard to electricity trading. The SD model is used to simulate utilities' choice to invest in three different divisions, namely information technology, education programs and marketing activities. Each of these aspects is described with the help of a feedback loop. Ochoa et al. (2002) state, that investments have an impact on the level of differentiation, segmentation and cost leadership.

For the management of water reservoirs and running-water power stations Van Ackere & Ochoa (2009) investigate different decision rules, however, pump storage units were not considered so far, because of their complex operation mode. A total of more than 80 strategies were evaluated. Price is determined by a merit order dispatch. Deregulated markets and regulated markets are considered. Result is that the introduction of strict guidelines, which aim to reduce the strategic use of hydropower plants leads to little use of hydropower plants. In this scenario operators only deplete the reservoir at very high prices. This results in high overall costs. Even a loss of welfare is observed.

A tabular model overview about the above mentioned publications and models is provided below.

TABLE 1: OVERVIEW OF CONSIDERED MODELS

Author (Year)	Research focus, particularity	Geographical Area	Scenario Time Horizon	Simulation Time Step	Institution
Regulated / monopolistic market					
Meadows et al. (1972)	Limits to growth	Global	Late 21st century		Massachusetts Institute of Technology (MIT)
Naill (1972)	Resources	Global			Massachusetts Institute of Technology (MIT)
Naill (1976)	Resources	Global			Massachusetts Institute of Technology (MIT)
Sterman (1987)	Expectation formation	-	-	-	Massachusetts Institute of Technology (MIT)
Ford et al. (1987)	Policy analysis	Columbia	20 years	Yearly	Washington State University, Pullman
Rego (1989)	Delay and financing	Argentina	1988 - 2003		National Council of Scientific and Technological Research of Argentina (CEMA)
Biair (1991)	Analytical models	-	-	-	Massachusetts Institute of Technology (MIT)
Dyner et al. (1993)	Residential energy policies	Medellin Metropolitan Area, Colombia	20 years	Yearly	Universidad Nacional de Colombia
U.S. Dept. of Energy (1993)	Energy analysis	U.S.A.	40 years	Quarterly	U.S. Department of Energy
Barney et al. (1995)	Sustainable development	Bangladesh	50 years	No information found	Millennium Institute, Arlington
Fiddman (1997)	Climate economy model	Generic	1960 – 2100 and 2300	No information found	Massachusetts Institute of Technology (MIT)
Ford (1997)	Role of simulation models	Pacific North West			Washington State University

Neubauer et al. (1997)	Models to study competition	Pacific North West	1993 - 2010	No information found	FNT Consulting, Portland
U.S. Dept. of Energy (1997)	Introduction to SD	-	-	-	U.S. Department Of Energy
Fiddman (1998)	Climate-economy model	Generic	1960 – 2100 and 2300	No information found	Ventana Systems, Inc., Sultan
Osgood (2003)	Renewable resources	-	-	-	-
Bassi (2006)	U.S. energy model	U.S.A.	2005 - 2050	Yearly	Millennium Institute, Arlington
Forest (2006)	Revisiting classic energy models	-	-	-	Leeds Metropolitan University, UK
Bassi (2007)	Behavior description	U.S.A.	2007 - 2050	Yearly	Millennium Institute, Arlington
Ochoa (2007)	Policy changes	Swiss	-	-	Universite de Lausanne, Switzerland
Bassi (2008)	Understanding energy issues	U.S.A.	2007 - 2050	Yearly	Millennium Institute, Arlington
Backus (2009)	Energy policy	-	-	-	Sandia National Laboratories, NM
Ochoa & Ackere (2009)	Dynamics of Swiss market	Swiss	2004 - 2024	Monthly	London Business School
Deregulated / liberalized market – Investment decisions, regulation					
Ford (1983)	Policy evaluation	Generic	1980 - 2005	Yearly	Los Alamos National Laboratory, New Mexico
Bunn & Larson (1992)	Investment behavior	England and Wales	1990 - 2030	Yearly	London Business School
Bunn et al. (1993)	Privatization	United Kingdom	1993 - 2030	Yearly	London Business School
Bunn & Larson (1994)	UK electricity investment	England and Wales	1994 - 2030	Yearly	London Business School
Dyner & Bunn (1997)	Energy policy Columbia	Columbia	15 years	Qarterly	Universidad Nacional de Colombia
Ford (1999)	Cycles in electricity markets	Western United States	1998 – 2018	3 months	Washington State University, Pullman
Larsen & Bunn (1999)	Strategic and regulatory risk	Generic	No simulation	No simulation	City University Business School, London
Gary & Larsen (2000)	Performance of out-of-equilibrium markets	Generic	1996 - 2020	Yearly	London Business School, Sussex
Dyner et al. (2001)	Planning to strategy	Generic	No simulation	No simulation	Universidad Nacional de Colombia
Ford (2001)	Study of power plant construction	California	8 years	Hourly	Washington State University

Qudrat-Ullah & Davidsen (2001)	Electricity supply, resources and pollution	Pakistan	2000 - 2030	Yearly	National University of Singapore
Arango et al. (2002)	Investment in generation capacities	Colombia	No limit	6 months	University of Bergen and Colombia
Vogstad et al. (2004)	Environmental policy	Nordic electricity market	30 years	Yearly	NTNU Trondheim
Kadoya et al. (2005)	Deregulation	PJM & ISO-NE	2005 -2025	6 blocks per day	Institute of electrical engineers of Japan
Qudrat-Ullah (2005)	Decision support	Pakistan	30 years	Yearly	York University, Toronto
Olsina et al. (2006)	Long term dynamics	Deregulated power markets	2000 - 2020	1/16 monthly	Univ. Nacional de San Juan, Argentina
Arango (2007)	Alternative regulation	Colombia	2000 - 2012	Daily, Monthly	Universidad Nacional de Colombia, Medellin
Dimitrovski et al. (2007)	Long term expansion	Western Electric Coordinating Council	2005 - 2035	Monthly	School of Electrical Engineering and Computer Science
Dyner et al. (2007)	Secure electricity supply	Colombia	10 years	Monthly	Universidad Nacional de Colombia, Medellin
Goidosch (2007)	Investment cycles	Germany	2004 - 2034	Monthly, Yearly	TU Berlin
Park et al. (2007)	Investment incentives	Korea	2006 - 2020	Yearly	Korean Electric Power Research Institute
Sanchez et al. (2007)	Generation expansion planning	Competitive markets			Universidad Pontificia Comillas, Madrid
Assili et al. (2008)	Capacity payment	Liberalized electricity markets	30 years	Yearly	Ferdowsi University of Mahhad, Iran
He et al. (2008)	Capacity mechanism analysis	Generic	30 years	Yearly	North China Electric Power University, Beijing
Sanchez et al. (2008)	Long-term investment	Generic	Generic	Yearly	Universidad Pontificia Comillas, Madrid
Acevedo & Aramburo (2009)	Capacity utilization	Deregulated power markets	Not specified	Yearly	Universidad Nacional de Colombia
Jäger et al. (2009)	Energy policy	German electricity market	30 years	Yearly	EIFER, Karlsruhe
Pereira & Saraiva (2009)	Expansion planning	Competitive markets	15 year horizon	Hourly	Institut Superior de Engenharia de Coibra,

					PT
Syed Jalal & Bodger (2010)	Generation expansion	New Zealand	2010 - 2050	No information found	University Tenaga Nasional Putrajaya, Malaysia
Tan et al. (2010)	Evaluating risky projects	Generic	20 years	Monthly	University of Texas, Austin
Hasani & Hosseini (2011)	Capacity mechanisms	Generic	2010 - 2040	Hourly	Sharif University of Technology, Tehran
Deregulated / liberalized market – New market design/structure and components/market power					
Bunn et al. (1997)	Latent market power	United Kingdom	1994 - 2004	No information	London Business School
García-Álvarez et al. (2005)	Effects of deregulation	Spain	72 days	Hourly	University of La Coruna
Vogstad (2005b)	Market design	Sweden, Norway	2005 - 2020	Secondly	Norwegian University of Science and Technology
Ford (2006)	Impact of carbon market on electricity system	Western electricity council (WECC)	2005 - 2025	Monthly	Washington State University, Pullman
Ford et al. (2007)	Price patterns for certificates	Northwestern U.S.A.	2006 - 2020	Monthly	Washington State University, Pullman
Ford (2008)	Reduction in carbon dioxide emissions	Western electricity council (WECC)	2005 - 2025	No information found	Washington State University, Pullman
Transmission grid					
Ojeda & Garces (2007a)	Merchant interconnection	Generic	20 years	Yearly	Bremer Energie Institut, Germany Instituto de Energía Eléctrica, Argentinia
Ojeda & Garces (2007b)	Dynamics of Swiss electricity market	Generic	20 years	yearly	Bremer Energie Institut, Germany Instituto de Energía Eléctrica, Argentinia
Ojeda et al. (2009)	Transmission interconnections	Generic	20 years	Yearly	Instituto de Energia Electrica, Argentina
Dyner et al. (2011)	Electricity market integration	Latin America	2010 - 2025	Monthly	Universidad Nacional de Colombia
Extensive models					
Grobbel (1999)	Competition in electricity generation	Germany and neighboring countries	15 years	Weekly	University of Oldenburg
Turk & Weijnen (2002)	Analyzing market performance	Generic	No information found	No information found	Delft University of Technology
Botterud (2003)	Long-term planning	Generic	20 – 50 years	Yearly	NTNU (Norway) and MIT (USA)

Dimitrovski et al. (2004)	Investment and growth in electric power systems	Western US & West Africa	2000 - 2025	Hourly	Washington State University, Pullman
Olsina (2005)	Long-term dynamics	Generic	20 years	Monthly	Universidad Nacional de San Juan, Argentina
Vogstad (2004)	Nordic electricity market	Nordic Electriciy Market	30 years	Weekly	Norwegian University of Science & Technology, Trondheim
Pasaoglu & Or (2006)	Liberalized electricity market	Generic	20 years	Monthly	Bogazici University, Istanbul
Dimitrovski et al. (2007)	Long-term modeling	Western Electric Coordination Council	20 years	Hourly	Washington State University
Hui (2009)	Transmission Investments	Generic	20 years	Yearly	Washington State University
Sanchez (2009)	Long-term planning	Generic	20 years	Yearly	Universidad Pontificia Comillas de Madrid
Other models					
Vlahos (1998)	Electricity markets	Generic	Defined by user	Defined by user	London Business School
Franco et al. (2000)	Training traders	Colombia	10 years	Quarterly (4 per year)	Universidad Nacional de Colombia, Medellin
Franco et al. (2001)	Strategy and risk management	Colombia	10 years	Quarterly (4 per year)	Interconexion Electrica E.S.P.
Ochoa et al. (2002)	Strategic electricity trading	Generic	No information found	No information found	Universidad Nacional de Colombia
Dyner et al. (2003)	Simulation for organizational learning	Generic	No information	No information	Universidad Nacional de Colombia
Dyner et al. (2009)	Games for electricity traders	Colombia	10 years	Quarterly (4 per year)	Universidad nacional de Colombia, Medellin
van Ackere & Ochoa (2010)	Hydro-energy reservoir	Generic	1 year	Hourly	Université de Lausanne, Switzerland
Pasaoglu (2011)	Educational tool	Generic	20 years	Monthly	Istanbul Kultur University, Turkey

4. SUMMARY AND OUTLOOK

The method SD is widely used for electricity market modeling. Generally, system-wide research questions such as the investigation of cyclic investment behavior in generation capacity dominate. However the modeling of selected aspects of electricity markets is supported by the capability to describe decision processes descriptively by considering the concept of bounded rationality. Furthermore, "imperfect foresight" such as uncertainties during capacity expansion planning supports realistic models. Moreover unlike most alternative methods, qualitative aspects can easily be incorporated into SD models, and therefore SD is an appropriate method for modeling electricity markets.

By the help of the presented review, three major trends in SD modeling could be identified: Firstly, SD models are increasingly combined with other methods: E.g. Pereira & Saraiva (2009, 2010, 2011) combine SD with generic algorithms, Acevedo & Aramuro (2009), Vogstad (2005b) incorporate experimental economics, Pasaoglu (2006) integrates an analytical hierarchy processes, Dyner et al. (2011) implement an iterative algorithm, Tan et al. (2010) use the method of decision trees, Sanchez et al. (2008) combine SD with game theoretical approaches and Butterud (2003) and Arango (2007) consider the real options approach.
Secondly, models with stochastic variables can be found progressively. For example Vogstad (2006), Butterud (2003) and Olsina et al. (2006) build on variable distributions by applying Monte Carlo Simulations within their models.
Thirdly, models are more and more detailed and simulate aspects such as new markets designs: E.g. Vogstad et al. (2002) model CO2-certificates, Vogstad (2005b) and Ford et al. (2007) model green electricity certificates and Anderson & Parker (2011) model the integration of renewable energy sources and the use of storages.

Due to the turnaround in energy policy, decentralized electricity generation, consideration of grid restrictions (see Dimitrovski et al. (2007)) or the demand side might gain in importance. Another emerging topic is the future role of storage power stations, which will probably gain in importance in SD modeling. This comes along with smaller simulation steps and high-resolution RES feed-in profiles. These aspects might be included in SD models in the future.

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