UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL

INSTITUTO DE PESQUISAS HIDRÁULICAS

SIMULAÇÃO E DIMENSIONAMENTO ÓTIMO DE SISTEMAS AUTÔNOMOS HÍBRIDOS COM RESERVATÓRIOS HIDRELÉTRICOS

FAUSTO ALFREDO CANALES VEGA

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Orientadores:	**Prof. Dr. Alexandre Beluco**
	Prof. Dr. Carlos André Bulhões Mendes

Banca Examinadora

Prof. Dr. Luiz Augusto Magalhães Endres	IPH/UFRGS
Prof. Dr. Elton Gimenez Rossini	UERGS
Prof^a. Dr^a. Andrea Fischer	IFSUL-Pelotas

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“You write your truth
and I'll write mine
one man's ceiling's
another man's sky high”
JBJ, RS

“[...] carpe diem, quam minimum credula postero.”
Horacio
(Carmina, 11.1)

Dedico este trabajo a mis padres, a mis hermanos y hermanas, y a Lila.

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RESUMO

O interesse mundial e os investimentos em fontes renováveis de energia têm aumentado consideravelmente nos últimos anos. Estas tecnologias têm a vantagem de aproveitar os recursos disponíveis localmente, reduzindo a dependência de fontes externas. Entretanto, um dos principais problemas associados a muitas das tecnologias de energias renováveis é sua imprevisibilidade ou intermitência. O armazenamento de energia é a técnica mais utilizada para moderar estas intermitências. Para aproveitamento em grande escala, os reservatórios hidrelétricos (de usinas hidrelétricas convencionais com reservatório e usinas hidrelétricas reversíveis) representam a tecnologia mais madura e amplamente aproveitada para armazenamento de energia elétrica na forma de energia potencial no volume de água. Isto faz destes uma opção importante a ser incluída no projeto de um sistema autônomo híbrido de geração de energia. Segundo diferentes autores consultados, o *software* HOMER (*Hybrid Optimization Model for Electric Renewables*) é a ferramenta mais amplamente utilizada em pesquisas relacionadas à simulação e configuração ótima deste tipo de sistemas.

Esta tese apresenta um conjunto de procedimentos para determinar, em nível de pré-viabilidade, a configuração ótima (em termos do custo presente líquido) e o conjunto de arranjos viáveis de um sistema autônomo de geração de energia incluindo fontes renováveis intermitentes e reservatórios hidrelétricos.

O *software* HOMER é aplicado na simulação e avaliação dos sistemas híbridos dos estudos de caso hipotéticos do presente trabalho, utilizados para validar os métodos propostos. Estes exemplos foram criados a partir de dados reais relacionados ao Estado de Rio Grande do Sul. Os procedimentos descritos são aplicáveis a qualquer região do mundo onde exista um local com potencial para reservatórios hidrelétricos, assim como dados de disponibilidade e custos relacionados a fontes renováveis intermitentes.

Além de determinar a configuração ótima e o conjunto de arranjos viáveis, os resultados obtidos indicam que os procedimentos descritos podem ajudar na definição da melhor utilização de um local com potencial hidrelétrico. Igualmente, permitem estimar a quantidade de eletricidade excedente que poderia ser recuperada através de usinas reversíveis. Os resultados mostram que configuração ótima depende de muitos fatores, tais como restrições hidrológicas, a carga a ser atendida e o custo de geração de cada fonte.

Palavras-chave: *Reservatórios hidrelétricos, Usinas reversíveis, Sistemas autônomos híbridos de geração, Energias renováveis, Armazenamento de energia, Software HOMER, Estudos de pré-viabilidade.*

ABSTRACT

Global interest and investments in renewable energy sources has increased considerably in recent years. These technologies have the advantage of using locally available resources, reducing dependence on external energy sources. However, most renewable energy technologies suffer from an intermittent characteristic due to the diurnal and seasonal patterns of the natural resources needed for power generation. Energy Storage is the most used technique to buffer this intermittency. For large-scale applications, hydropower reservoirs (of conventional and pumped storage plants) are the most mature and the most widely employed technology for electricity storage in the form of potential energy. For this reason, a hydropower reservoir is a suitable option to consider including in an autonomous hybrid power system. According to many authors, the HOMER model (Hybrid Optimization Model for Electric Renewables) is the most widely used tool in research studies related to simulation and optimal design of this type of systems.

This thesis presents some procedures to define, as a pre-feasibility assessment, the optimal configuration (in terms of Net Present Cost) and set of feasible designs of an autonomous hybrid power system that includes intermittent renewable energy sources and hydropower reservoirs.

The HOMER software is used for simulating and evaluating the hybrid power systems of the hypothetical case studies, used to validate the proposed methods. These examples were created based on real data related to the State of Rio Grande do Sul, Brazil. The procedures described can be adapted to any other region of the world where exists a site suitable for the construction of hydropower reservoirs, along with available data regarding intermittent renewable sources and generation costs.

Besides defining the optimal configuration and the set of feasible designs, the results indicate that the procedures explained could help in the definition of the best use of a site with hydropower potential. Likewise, these methods can also be used to estimate how much excess electricity can be recovered by means of pumped storage hydropower. The results show that the optimal system design depends on many factors such as hydrological constraints, average load to serve and energy cost of each source.

Keywords: *Hydropower reservoirs, Pumped storage hydropower, Autonomous hybrid power systems, Renewable energies, Energy storage, HOMER software, Pre-feasibility assessment.*

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LISTA DE ABREVIATURAS

***Observação**: Em itálicas e negritas, abreviaturas alternativas em inglês.*

A	Ampere. Unidade de medida para intensidade de corrente elétrica
AC	Corrente alternada
Ah	Ampere·hora
ANEEL	Agência Nacional de Energia Elétrica
CA	Corrente alternada
CAES	Armazenamento de energia por ar comprimido
C_B	Capacidade da bateria em Ah
CC	Corrente contínua
CF	Fator de capacidade
CO2	Dióxido de carbono
COE	Custo de produção de energia elétrica
d	Dia
DC	Corrente contínua
E	Energia gerada
E_S	Energia armazenada
GW	Gigawatt, 10^9 Watts. 1 Watt = 1 joule por segundo (1 J/s)
GWh	Gigawatt·hora. Equivale a 10^9 Wh ou $3{,}6\times10^{12}$ joules
H	Altura de queda
h	Hora
HOMER	*Hybrid Optimization Model for Electric Renewables*
Hz	Hertz. Unidade do Sistema Internacional de medidas para frequência
I	Intensidade de corrente elétrica
IEA	*International Energy Agency*
IRENA	Agência Internacional de Energia Renovável
J	Joule. Unidade do Sistema Internacional para trabalho ou energia
kW	Quilowatt, 10^3 Watts. 1 Watt = 1 joule por segundo (1 J/s)
kWh	Quilowatt·hora. Equivale a 1.000 Wh ou $3{,}6\times10^6$ joules
MW	Megawatt, 10^6 Watts. 1 Watt = 1 joule por segundo (1 J/s)
MWh	Megawatt·hora. Equivale a 1.000.000 Wh ou $3{,}6\times10^9$ joules
N	Newton
NPC	Custo presente líquido (*Net Present Cost*)

O&M	Custos de operação e manutenção
ONS	Operador Nacional do Sistema Elétrico
P	Potência
P_{hyd}	Potência gerada pela turbina hidrelétrica
PROINFA	Programa de Incentivo às Fontes Alternativas de Energia Elétrica
PSH	Usina hidrelétrica reversível (*Pumped Storage Hydropower*)
Q	Vazão
RPM	Rotações por minuto
RS	Rio Grande do Sul, Brasil
SIN	Sistema Interligado Nacional
t	Tempo
UHER	Usina hidrelétrica reversível
V	Voltagem, volts
Vol	Volume útil do reservatório
η	Eficiência de conversão de energia
η_{hyd}	Eficiência de conversão de energia da turbina hidrelétrica

1. INTRODUÇÃO GERAL

O interesse mundial e os investimentos na geração de energia a partir de fontes renováveis têm aumentado consideravelmente nos últimos anos. Entre os principais motivos podem-se citar: preocupações ambientais, encarecimento dos derivados do petróleo, contínuo desenvolvimento tecnológico, o constante crescimento da população mundial e consequente incremento na demanda de energia, especialmente nos países industrializados. O uso das fontes de energia renovável oferece a vantagem de aproveitar os recursos disponíveis localmente, reduzindo a dependência de fontes de energia externas. Adicionalmente, algumas das principais tecnologias (*e.g.*: energia solar, eólica e dos oceanos) reduzem a emissão de CO2 para a atmosfera, quando comparadas com centrais termelétricas convencionais.

Entretanto, um dos principais problemas associados a muitas das tecnologias de energias renováveis é a impossibilidade de prever o comportamento em tempo real da produção das plantas, devido à variabilidade sazonal (*e.g.:* hidrelétricas a fio d'agua), diária (*e.g.:* energia solar), e às vezes imediata (*e.g.:* energia eólica) destas fontes de energia. O problema desta imprevisibilidade, ou intermitência, conforme Vennemann *et al.* (2010), é que nas redes de distribuição a eletricidade fornecida deve coincidir com a carga durante todo o tempo. Este equilíbrio é necessário para garantir a qualidade do atendimento e a estabilidade da frequência na rede (geralmente 50 Hz ou 60 Hz). Assim, as flutuações devem ser compensadas através de outros tipos de geração, geralmente, usinas termelétricas com custo de produção de energia maior e emissão de poluentes.

Por esta razão, o setor elétrico de países como Estados Unidos considerou durante muito tempo que as energias renováveis nunca seriam capazes de contribuir significativamente ao atendimento da energia de base (geração permanente e contínua). Contudo esta percepção tem mudado e, segundo Estanqueiro *et al.* (2007) e Sovacool (2009), recentes pesquisas, projetos e experiências em todo o mundo têm demonstrado que, na atualidade, o problema não é a variabilidade ou intermitência *per se*, mas como esta imprevisibilidade pode ser mais bem prevista, administrada e mitigada.

Três possíveis soluções são citadas por Faias *et al.* (2009) para garantir o equilíbrio na rede entre a geração e a carga: (i) limitar a geração a partir de fontes renováveis, desperdiçando estes recursos e aumentando a geração termelétrica; (ii) exportar o excedente de energia gerada através da interligação do sistema, como é realizado no sistema interligado brasileiro, de complexa operação; (iii) a terceira solução, um dos principais objetos da presente tese, é armazenar o excedente de energia elétrica produzida para utilizá-la em períodos de grande demanda. Esta terceira solução, é o principal objetivo da presente tese.

Segundo Reis (2003), o emprego de sistemas de armazenamento é o conceito principal das técnicas mais conhecidas para aumentar a parcela de energia renovável em sistemas elétricos.

Para aproveitamento em grande escala, os reservatórios hidrelétricos (de usinas hidrelétricas convencionais com reservatório e usinas hidrelétricas reversíveis - UHER) são a tecnologia mais madura e amplamente utilizada para armazenamento de energia elétrica na forma de energia potencial no volume de água. Segundo Castronuovo e Usaola (2013), a coordenação entre energias renováveis intermitentes e reservatórios hidrelétricos pode ser realizada das seguintes formas:

- **Utilizando usinas reversíveis:** Estas centrais consistem em dois reservatórios situados em alturas diferentes, ligados por válvulas hidráulicas e condutos forçados. Estas centrais estão equipadas com máquinas que podem operar tanto para a geração de energia elétrica, turbinando a água contida em um reservatório superior, quanto para o armazenamento de energia elétrica excedente de outras fontes, bombeando novamente água desde o reservatório inferior para o superior. Em função do equipamento utilizado, a eficiência do ciclo completo (bombeamento/armazenamento/turbinamento) oscila entre 50 e 85%. Além de conseguir recuperar parte da energia que de se fosse de outra forma tivesse sido rejeitada, a capacidade de armazenamento e produção controláveis permite compensar os desvios na geração a partir de fontes renováveis intermitentes.
- **Coordenação com usinas hidrelétricas com reservatório:** Se outras fontes de energia renovável são capazes de atender a carga na rede, e considerando fatores de segurança baseados em previsões sólidas e análise de incertezas, é possível reduzir a geração hidrelétrica nestes períodos. Desta forma se facilita a recarga do reservatório, a fim de que este volume armazenado possa ser utilizado para o atendimento da carga quando estas fontes variáveis não estiverem disponíveis.

Esta capacidade de armazenamento dos reservatórios hidrelétricos faz destes uma opção importante a ser incluída no projeto de um sistema autônomo híbrido de geração de energia. Neste trabalho, utilizando uma definição similar à de Lukuyu and Cardell (2014), um sistema deste tipo será definido como aquele capaz de produzir eletricidade para sua operação autônoma (isolado, mas com opção de vender o excedente) a partir de duas ou mais tecnologias de geração, geralmente incluindo uma ou mais fontes renováveis, e seus dispositivos de armazenamento de energia correspondentes.

Nos trabalhos de Sinha e Chandel (2014) e Connolly *et al.* (2010) foram analisados, respectivamente, 19 e 37 programas de *software* para modelagem de sistemas híbridos de geração. Com base nos seus resultados e com milhares de usuários, o *software* HOMER (*Hybrid Optimization Model for Electric Renewables*) é a ferramenta mais amplamente utilizada em pesquisas relacionadas à simulação e configuração ótima deste tipo de sistemas. As principais razões para isto são que o HOMER está disponível gratuitamente (http://homerenergy.com – versões de avaliação por 15 dias, e a *Legacy* por tempo indefinido), é de fácil aprendizagem, conta com uma documentação detalhada e possui uma interface amistosa ao usuário.

Desenvolvido inicialmente pelo *U.S. National Renewable Energy Laboratory* – NREL, o *software* HOMER é descrito por Lambert *et al.* (2006) como um modelo computacional utilizado para auxiliar no projeto de sistemas de energia híbridos e facilitar a comparação de diferentes tecnologias de geração de energia (turbinas eólicas, hidrelétricas a fio d'água, baterias, painéis fotovoltaicos, etc.) através de uma série de aplicações. O HOMER modela o comportamento físico do sistema de energia e o seu custo de ciclo de vida, que inclui o custo de instalação e operação do sistema durante sua vida útil. O programa permite comparar diversas configurações de projeto baseadas em suas características técnicas e econômicas, e sua capacidade de realizar análises de sensibilidade auxilia a entender e quantificar os efeitos de incertezas ou de mudanças nos dados de entrada.

As três principais funções do HOMER são: (i) Simular a operação do sistema durante as 8760 horas do ano; (ii) Otimizar a configuração do sistema em termos do custo presente líquido; (iii) Realizar análises de sensibilidade, executando múltiplas otimizações para avaliar os efeitos de incertezas ou mudanças nos dados de entrada do modelo. Com base em Sinha e Chandel (2014), a Figura 1 apresenta uma representação esquemática do funcionamento do HOMER.

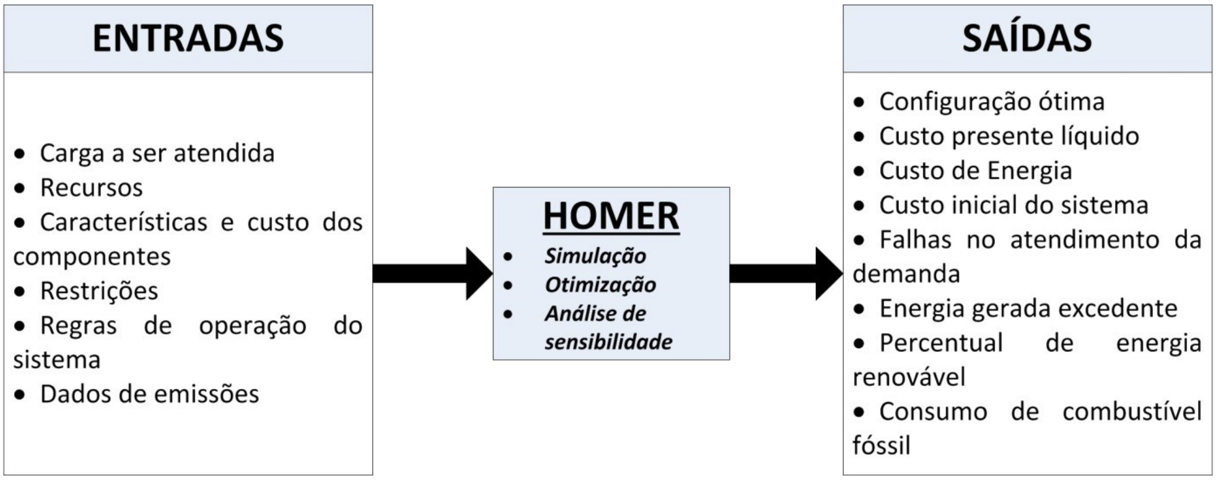

Figura 1. Representação esquemática do *Software* HOMER
(Fonte: Adaptado de Sinha e Chandel, 2014)

Algumas das principais limitações do HOMER são as seguintes: (i) a função de otimização é mono-objetivo (ou escalar), e visa minimizar o custo presente total do sistema; (ii) a variabilidade em períodos menores que uma hora não pode ser considerada; (iii) com exceção dos geradores a combustível, a produção de outros tipos de centrais não pode ser programada; (iv) alguns tipos de tecnologias renováveis não estão incluídos, entre estes, os reservatórios hidrelétricos. Das restrições anteriores, somente a última é de interesse para o presente trabalho; porém, segundo será explicado posteriormente neste documento, a capacidade de criar baterias elétricas personalizadas no *software* HOMER permite contornar esta limitação de forma efetiva. No Anexo A é incluída uma seleção de conteúdos extraídos do arquivo de ajuda do *software* HOMER, que descreve algumas das principais características do programa utilizadas nesta pesquisa.

Com base nestas considerações iniciais, e por causa de sua confiabilidade e recursos disponíveis, o HOMER foi selecionado como a ferramenta base a utilizar na solução do problema a ser tratado no presente trabalho: *Como determinar, de forma preliminar, a melhor configuração de um sistema híbrido autônomo de geração de energia elétrica que inclua fontes renováveis intermitentes e reservatórios hidrelétricos?*

1.1 Justificativa

A Agência Internacional de Energia Renovável (*International Renewable Energy Agency* – IRENA, 2014), formada por 130 países membros (entre eles o Brasil) e 38 em processo de ingresso, tem como um dos seus principais objetivos duplicar a parcela de energia total gerada a partir de fontes renováveis até 2030, conforme mostrado na Figura 2. Atualmente, a energia derivada de fontes renováveis corresponde a 18% da energia total consumida no mundo, sendo que metade deste parcial é originada a partir de biomassa tradicional (*e.g.:* bagaço de cana, madeira e carvão vegetal). Para reduzir a contribuição de gases de efeito estufa emitidos por este tipo de centrais de biomassa, a IRENA propõe utilizar técnicas modernas que permitem aumentar a eficiência na conversão de energia neste tipo de usinas (de <20% para quase 50%). Igualmente, entre as metas para 2030, a IRENA pretende triplicar a parcela de outros tipos de energias renováveis modernas, como biocombustíveis, centrais elétricas geotérmicas, eólicas e solares. Na geração de energia elétrica, a integração de algumas destas fontes renováveis (principalmente a solar e a eólica) é dificultada pela sua intermitência e imprevisibilidade.

Conforme Estanqueiro *et al.* (2007), a integração em grande escala de energias renováveis intermitentes em sistemas elétricos requer também um volume importante de reservatórios hidrelétricos com grande capacidade de geração. Em parágrafos anteriores foi descrito, com base no trabalho de Castronuovo e Usaola (2013), como os reservatórios hidrelétricos podem ser coordenados com energias renováveis intermitentes, permitindo um melhor aproveitamento e integração destas últimas. Os reservatórios hidrelétricos permitem controlar de forma efetiva a vazão que passa pelas turbinas em função da demanda de energia, contrário às usinas a fio d'agua, nas quais a capacidade de geração pode oscilar consideravelmente ao longo do ano, dependendo do regime de vazões.

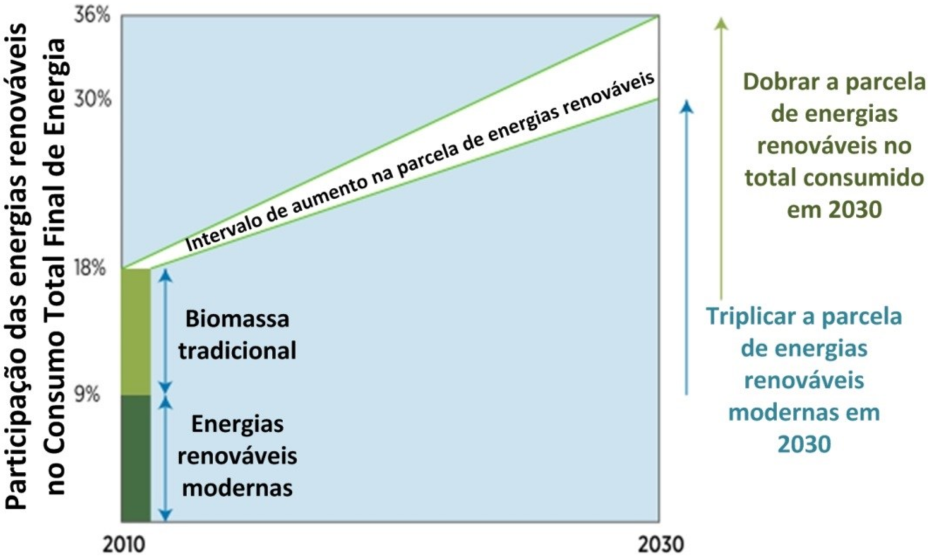

Figura 2. Expectativas para as energias renováveis no consumo global total de energia em 2030 (Fonte: Adaptado de IRENA, 2014)

A configuração e dimensionamento adequado de sistemas híbridos autônomos de geração de energia elétrica são essenciais para a utilização eficiente dos recursos energéticos renováveis, reduzindo os custos de instalação e minimizando os custos de produção de eletricidade. Por esta razão, programas de *software* para modelagem deste tipo de sistemas são ferramentas importantes nos estudos correspondentes de viabilidade técnica, econômica e ambiental.

Entre as ferramentas citadas por Sinha e Chandel (2014) para modelagem de sistemas híbridos, pelo menos quatro delas permitem modelar geração hidrelétrica a fio d'água (HOMER, iHOGA, iGRHYSO e IPSYS), mas nenhuma com reservatório. Já no trabalho de Connolly *et al.* (2010), são citados o *ProdRisk* e o *EnergyPlan*, mas o primeiro só está disponível comercialmente para aplicações em grande escala (CONNOLLY, 2012) e o segundo não possui um módulo de otimização, um dos principais interesses deste trabalho. Contudo, e como demonstrado ao longo da presente tese, os processos de armazenamento e entrega de energia por meio de reservatórios hidrelétricos têm analogias com os das baterias elétricas. O *software* HOMER foi selecionado como a ferramenta principal a utilizar no presente trabalho, devido às seguintes razões: (i) é uma ferramenta amplamente testada e confiável em estudos relacionados a sistemas híbridos de geração; (ii) a versão *Legacy* v2.68 está disponível gratuitamente; (iii) permite a criação de baterias com características especificadas pelo usuário, condição fundamental para a representação eficaz de um reservatório hidrelétrico como bateria equivalente; (iv) possui um módulo de otimização (v) permite realizar diretamente análises de sensibilidade.

Os métodos descritos na presente tese são aplicáveis a qualquer região do mundo onde exista um local com potencial para reservatórios hidrelétricos, assim como dados de disponibilidade e custos relacionados a fontes renováveis intermitentes. Os estudos de caso hipotéticos utilizados para validar os métodos explicados neste trabalho foram criados a partir de informações reais relacionadas ao Estado de Rio Grande do Sul (RS). Os dados dos reservatórios foram extraídos de Beluco (2012), que identificou três locais com potencial para a implantação de UHER na extremidade sul da Serra Geral, no Litoral Norte do Estado. Dois dos sistemas propostos pelo autor são utilizados em capítulos seguintes deste documento. A Figura 3 mostra as curvas Cota x Área x Volume desses reservatórios, elaboradas com base nas tabelas apresentadas por Beluco (2012).

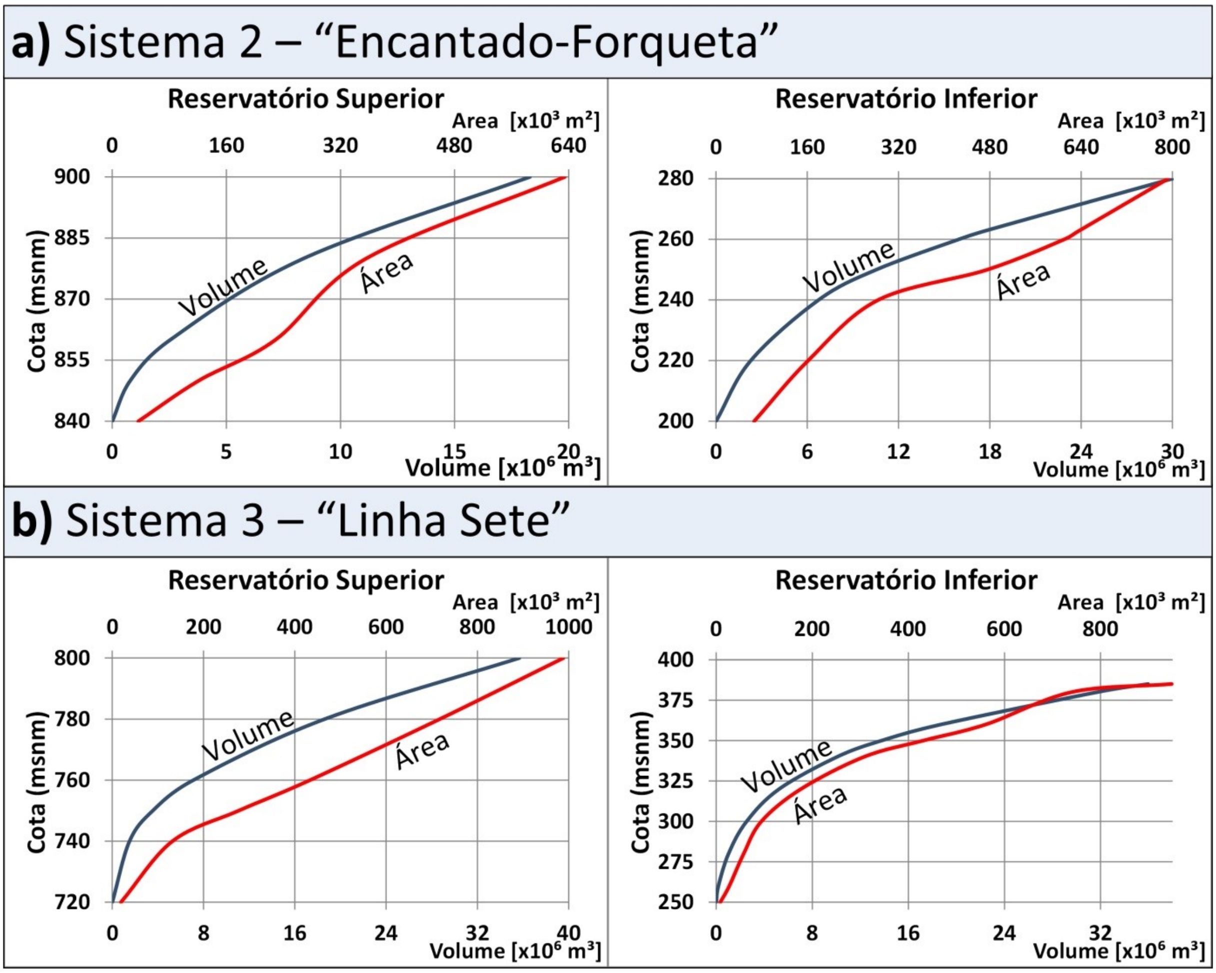

Figura 3. Curvas Cota x Área x Volume dos reservatórios utilizados nos estudos de caso

Apenas para uma breve contextualização, é interessante mencionar que a riqueza de recursos hídricos no Brasil permitiu a construção de muitas usinas hidrelétricas com grandes reservatórios. Estas plantas são o núcleo do Sistema Interligado Nacional (SIN), que exige um plano de operação complexo e uma rede de transmissão de aproximadamente 100.000km. Menos de 2% da energia requerida pelo país encontra-se fora do SIN, em pequenos sistemas isolados situados principalmente na região amazônica. Aproximadamente 90% da produção total de energia do SIN correspondem à energia hidrelétrica (REIS, 2003).

A complementariedade regional quanto ao regime hidrológico e dos ventos, a eficiência do SIN e a abundância de recursos são as principais razões pelas quais a participação das UHER é praticamente inexistente no Brasil. Galhardo (2012) explica que empreendimentos de UHER, ou outras tecnologias de armazenamento de energia, poderiam tornar-se urgentes nos próximos anos, dada à tendência e incentivos para diversificar as fontes da matriz nacional (*e.g.*: o programa PROINFA, instituído em 2002) e a diminuição da regularização de vazões em novas usinas. Conforme dados levantados por Preite Sobrinho (2014), somente dez das 42 hidrelétricas leiloadas no Brasil entre 2000 e 2012 incluem reservatórios de regularização.

1.2 Hipótese e objetivos

A hipótese do presente trabalho a ser testada é a seguinte: **É possível determinar a configuração mais eficiente de um sistema híbrido autônomo de geração de energia elétrica que inclua fontes renováveis intermitentes e reservatórios hidrelétricos.**

Com base no estabelecido anteriormente, os objetivos que se desejam atingir na presente tese são os seguintes:

Objetivo geral:

- Determinar, em nível de pré-viabilidade, a configuração ótima (em termos do custo presente líquido) e o conjunto de arranjos viáveis de um sistema autônomo de geração de energia incluindo fontes renováveis intermitentes e reservatórios hidrelétricos.

Objetivos específicos:

- Demonstrar que reservatórios hidrelétricos podem ser eficazmente representados através de baterias equivalentes.
- Comparar o desempenho de usinas hidrelétricas com reservatório e usinas hidrelétricas reversíveis em um sítio onde ambas as tecnologias poderiam ser aproveitadas.

- Quantificar a capacidade de recuperação de energia excedente e o incremento do fator de capacidade de centrais renováveis mediante usinas hidrelétricas reversíveis.

1.3 Estrutura da tese

Além deste capítulo introdutório e um capítulo com as conclusões e considerações finais, esta tese é composta por quatro artigos independentes e complementares entre si. Esta organização está contemplada nas disposições dos artigos 3º e 5º da Resolução nº 093/2007 da Câmara de Pós-graduação da UFRGS. Por causa da independência de cada um destes artigos, alguns conceitos devem ser mencionados em mais de um deles. Para uma melhor compreensão do conteúdo deste documento, a Figura 4 mostra as relações de métodos e conceitos entre os capítulos. Assim sendo, a estrutura da presente tese é a seguinte:

- **Capítulo 1 – Introdução geral.** Inclui os conceitos mais relevantes da presente tese, assim como a justificativa, hipótese e objetivos do trabalho.
- **Capítulo 2 – Usinas hidrelétricas reversíveis no Brasil e no mundo: aplicação e perspectivas.** Apresenta uma revisão da literatura sobre o armazenamento de energia elétrica através de UHER e o estado desta tecnologia no cenário global e brasileiro. No documento se comparam brevemente as principais tecnologias disponíveis para armazenamento de energia elétrica.
- **Capítulo 3 – Modeling pumped hydro storage with the micropower optimization model (HOMER) [DOI: 10.1063/1.4893077].** Descreve e valida um método para modelar UHER no *software* HOMER, através de um exemplo com parâmetros controlados. A UHER é representada por uma bateria equivalente.
- **Capítulo 4 – Modeling a hydropower plant with reservoir with the micropower optimization model (HOMER).** Descreve e valida um método para modelar usinas hidrelétricas com reservatório no *software* HOMER, adaptando o procedimento do capítulo anterior para este propósito. O estudo de caso utilizado para validação foi criado com base em dados do RS. O reservatório foi modelado com base no “Sistema 2” ou “Encantado-Forqueta”, segundo dados na Figura 3a.
- **Capítulo 5 – Optimization of autonomous power systems with hydropower reservoirs and intermittent renewable sources.** Aproveita os métodos anteriores para determinar a configuração ótima de um sistema híbrido autônomo de geração de energia elétrica contendo fontes renováveis intermitentes e reservatórios hidrelétricos. Apresenta também procedimentos para: (i) comparar o desempenho de ambos os tipos de reservatórios hidrelétricos; (ii) utilizar o HOMER na

estimativa da capacidade de recuperação de energia excedente através de UHER. O estudo de caso utilizado para validação foi criado com base em dados do RS, e os reservatórios hidrelétricos foram modelados com base no "Sistema 3" ou "Linha Sete", segundo dados na Figura 3b.

- **Capítulo 6 – Conclusões e Recomendações:** Apresenta as principais conclusões da pesquisa, com base nos capítulos anteriores. Neste capítulo se examina se os objetivos foram atingidos e se é possível responder afirmativamente à pergunta que constitui a hipótese. São incluídas recomendações para futuros trabalhos.
- **Anexos:** Uma seleção de extratos da documentação de HOMER, descrevendo algumas das principais funções do modelo utilizadas no presente trabalho.

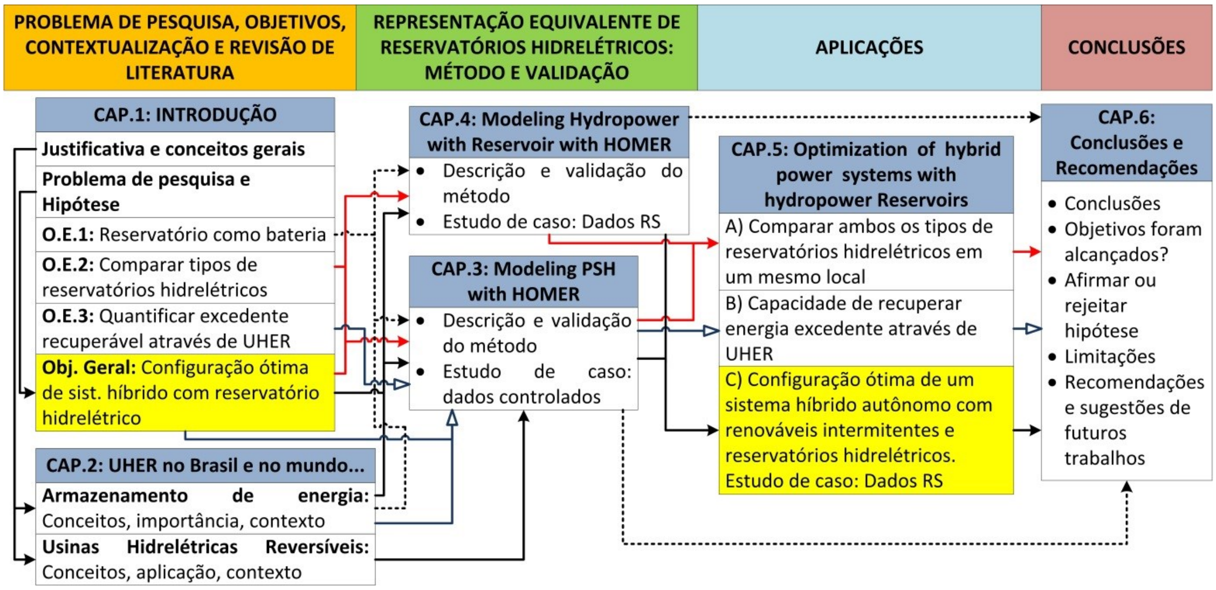

Figura 4. Relações de métodos e conceitos entre os capítulos

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MODELING A HYDROPOWER PLANT WITH RESERVOIR WITH THE MICROPOWER OPTIMIZATION MODEL (HOMER)

Fausto A. Canales[1], Alexandre Beluco[2], Carlos André B. Mendes[3]

Instituto de Pesquisas Hidráulicas (IPH), Universidade Federal do Rio Grande do Sul (UFRGS),
Av. Bento Gonçalves, 9500 CEP: 91501-970 - Porto Alegre - RS - Brasil

ABSTRACT

A hydropower plant with reservoir is an interesting option to consider in hybrid power systems, because it helps dealing with the great seasonal variability and daily intermittence of other renewable energies. The hybrid optimization model for electric renewables (HOMER) is extensively used in researches related to these systems, but it does not include a specific option for modeling a hydropower plant with reservoir. This paper describes a method for modeling a hydropower plant with reservoir in HOMER, by adapting an existing procedure used for modeling pumped-storage hydropower with this software tool. An example with two scenarios created from data related to Rio Grande do Sul, Brazil, is presented for illustrating and validating the method explained in this document. The results validate the method by showing a direct correspondence between an equivalent battery and the reservoir. The refill of the reservoir, its power output as a function of the flow rate, and installed hydropower capacity are effectively simulated, indicating an adequate representation of a hydropower plant with reservoir is possible in HOMER.

Keywords: *hydropower with reservoir, hybrid power systems, HOMER software, computational simulation, feasibility studies.*

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[1] Civil Eng., Master. Instituto de Pesquisas Hidráulicas, Universidade Federal do Rio Grande do Sul, Av. Bento Gonçalves, 9500, CEP 91501-970 - Porto Alegre – RS, Brasil. E-mail: fausto.canales.v@gmail.com

[2] Dr.Eng. Professor. Instituto de Pesquisas Hidráulicas, Universidade Federal do Rio Grande do Sul, Av. Bento Gonçalves, 9500, CEP 91501-970 - Porto Alegre – RS, Brasil (Corresponding author). E-mail: albeluco@iph.ufrgs.br

[3] Dr.Eng. Professor. Instituto de Pesquisas Hidráulicas, Universidade Federal do Rio Grande do Sul, Av. Bento Gonçalves, 9500, CEP 91501-970 - Porto Alegre – RS, Brasil.

INTRODUCTION

Hydropower with reservoir is one of the most mature renewable energy technologies. By storing a significant volume of water at a high elevation, the reservoir successfully operates as an electricity storage device, relying on gravity to transform the potential energy into kinetic energy when water falls to a lower elevation, using this flow to drive a turbine for generating electricity in the process. Besides these characteristics, the dispatchable nature of hydropower with reservoir turns it into an appropriate option to consider as a component in hybrid power systems.

For this document, using a similar definition to the one provided by Lukuyu and Cardell (2014), a hybrid power system can be defined as an usually stand-alone system that produces electricity from two or more generating technologies, typically including one or more renewable energy sources and their corresponding storage devices. Hydropower reservoirs can considerably increase the efficiency of hybrid power systems, reducing emissions produced by non-renewable power plants, and allowing a better integration of intermittent renewable sources like wind power or solar energy.

Based on the work of Sinha and Chandel (2014), it can be listed at least four software tools for hybrid energy systems analysis that include hydropower among the components of the arrangement:

- Hybrid Optimization Model for Electric Renewables (HOMER – http://homerenergy.com)
- Improved Hybrid Optimization by Genetic Algorithm (iHOGA – http://www.unizar.es/rdufo).
- Improved Grid-connected Renewable Hybrid Systems Optimization (iGRHYSO – http://www.unizar.es/rdufo/grhyso.htm).
- Integrated Power System (IPSYS – http://www.cee.elektro.dtu.dk/research/projects/36_IPSYS).

As of today, none of the items of that list includes the option of specifically modeling a hydropower plant with reservoir. From these options, according to Sinha and Chandel (2014) and Connolly *et al.* (2010), HOMER is the tool most extensively used in researches related to hybrid power systems, with thousands of users around the world.

The HOMER software tool, also known as the "Micropower Optimization Model", is used for simulating and optimizing hybrid stand-alone or grid-connected power systems. As explained by Lambert *et al.* (2006), the optimal system configuration in HOMER is the combination that satisfies the constraints specified by the user, at the lowest total net present cost. The software allows evaluating different system configurations comprising several technologies for electricity generation like: run-of-river hydropower, batteries, wind turbines, photovoltaic arrays, internal combustion engine generators, etc., for serving electric or thermal loads.

In a similar work to that of Sinha and Chandel (2014), the EnergyPLAN model (available at http://www.energyplan.eu) is briefly described by Conolly *et al.* (2010). EnergyPlan includes the possibility of assigning a storage capacity for the hydropower plant in terms of GW·h, in a similar approach as in the method explained in this paper. EnergyPLAN includes a vast variety of aspects required for national or regional energy systems planning, and it can be used for technical and market exchange analysis as well as in feasibility studies. However, unlike HOMER, it does not perform sensitivity analysis nor automatically selects the optimal size of the components of the system based on options given by the user. EnergyPLAN also needs the external input files of the hour-by-hour distribution data for each renewable energy source, while HOMER can synthesize these values from solar or wind resources monthly averages.

Within this context, this paper describes a method for modeling a hydropower plant with reservoir in HOMER. This is possible by making some modifications to the procedure explained in a previous work by Canales and Beluco (2014), in which they created an equivalent battery for modeling a pumped hydro in HOMER. The next section of this document explains the method adopted that would allow to represent a hydropower plant with reservoir, based on its main features, available resources and some other considerations. To validate the method, an example of a hybrid power system including a hydropower plant with reservoir is modeled in HOMER, and its results are presented and discussed. The example was created using data related to Rio Grande do Sul, a southern state of Brazil. The software version used for this work was the HOMER Legacy Version 2.68, freely available at http://homerenergy.com/. Future releases or custom versions of HOMER (and other similar software tools) might include specific components to model hydropower reservoirs, but the Legacy version was selected due to its universal access.

MODELING A HYDROPOWER PLANT WITH RESERVOIR IN HOMER

The existence of a reservoir in a hydropower plant installation allows hydropower to be adaptive and flexible, because electricity generation can be scheduled and optimized (Yüksel, 2010). The run-of-river operation can be used for baseload generation, while the reservoir stores potential energy for using it to serve higher or peak loads. This dispatchability makes the hydro with reservoir an interesting alternative to consider in hybrid power systems, especially because of the great seasonal variability and daily intermittence of other renewable energies such as solar energy or wind power. This section describes the considerations and method adopted to model a hydropower plant with reservoir in HOMER, by making some modifications to the procedure explained in Canales and Beluco (2014),

In HOMER, the first step for creating the model of a system is to select the equipment to consider in the design. The three HOMER components needed for modeling a hydropower plant with reservoir are: the hydro installation, the converter and a battery created specifically to represent the main features of the hydropower plant and its reservoir. The corresponding considerations for each one of these elements are explained in the remainder of this section.

Hydro installation

A hydro turbine is modeled in HOMER as a device that transforms the power of falling water into alternating (AC) or direct (DC) current at a constant efficiency, without the capacity to store water or modulate its power output. As explained by Lambert *et al.* (2006), the power obtainable from falling water is proportional to the product of the stream flow and the available head (the vertical distance through which water falls). Information related to the stream flow available to the turbine each hour comes from the hydro resource data, which can be synthetized by HOMER from monthly averages or by importing hourly data from a file. For each hour of the simulation, HOMER calculates the power output of the hydro turbine through the expression:

$$P_{hyd} = \eta_{hyd} \times H \times \rho_{H2O} \times g \times Q \,/\, (1000W/kW) \tag{1}$$

In Equation (1), P_{hyd} is the power output of the hydro turbine (kW), η_{hyd} the hydro turbine efficiency (%), H the effective head [m], ρ_{H2O} the density of water (1000 kg/m^3), g the gravitational acceleration (9.81 m/s^2) and Q is the flow rate through the turbine (m^3/s).

In order to allow modeling a hydropower plant with reservoir in HOMER, the method explained in this article requires the following conditions for the hydro turbine:

1. Besides the battery representing the reservoir, the run-of-river hydro installation must be the only equipment on the DC bus. This will guarantee that the battery inputs and outputs will simulate the water flow rates being stored or leaving the reservoir.
2. All losses must be included in the efficiency with which the hydro system converts the energy in the water to electricity. Therefore, pipe head loss must be set to zero. This is to ensure that each cubic meter of water, both through the turbines as in the reservoir, represents the same amount of energy in terms of kilowatt-hours (kW·h).
3. For the hydro resource input, the residual flow (the quantity of water that must remain uninterrupted in the watercourse for ecological reasons) should be deducted before entering or importing the flow rates in HOMER.
4. The design flow rate and its corresponding minimum and maximum flow rates should encompass the whole range of available stream flows.

Battery representing the reservoir

Batteries are modeled in HOMER as devices capable of storing a specific quantity of DC electricity, with a particular round-trip efficiency. The software considers that the battery properties remain the same during its lifetime, without suffering the effects of any external factor such as temperature. As explicated in the paper by Canales and Beluco (2014), the fact that the reservoir stores energy and supplies it on demand, justifies its modeling as a battery in HOMER. By creating a battery, the user is able to define a high capacity along with a specific voltage, and it allows modeling the reservoir as one huge battery.

According to the aforementioned authors, for a hydro with storage, the total stored energy E_S (in kW·h) in the volume of the reservoir Vol (in m^3) can be described by the equation:

$$E_S = 9.81 \times \eta \times H \times Vol / 3600 \quad (2)$$

For a battery with a fixed voltage V and capacity C_B (in Ampere·hours, A·h) independent of its discharge current, its stored energy (in kW·h) can be found by the equation:

$$E_S = V \times C_B / 1000 \quad (3)$$

When the voltage V is considered as fixed, the power delivered by the battery (in kW) is proportional to the current I (in A), and is calculated by the expression:

$$P_{bat} = V \times I / 1000 \quad (4)$$

Based on these equations, the method explained in this paper requires the following conditions and considerations for the battery representing the reservoir, in order to allow modeling a hydropower plant with reservoir in HOMER:

1. Besides the run-of-river hydro installation, the battery representing the reservoir must be the only equipment on the DC bus. This will guarantee that the battery inputs and outputs will simulate the water flow rates being stored or leaving the reservoir.
2. A reference voltage for the equivalent battery must be selected. This will allow combining equations (2) and (3) to find the C_B value (in A·h) of the equivalent battery, proportional to the active storage volume of the reservoir.
3. Create an equivalent battery in HOMER with the following characteristics:
    a. Constant capacity C_B for any discharge current,
    b. The reference voltage previously selected,
    c. Round trip efficiency 100% and minimum state of charge 0%,
    d. A maximum charge current at least proportional to the maximum stream flow expected,
    e. A high maximum charge rate (many times the calculated value),
    f. Float life and cycles to failure of the equivalent battery related to the planning horizon and operation regime, or use other considerations.
4. Losses due evaporation, withdrawal or infiltration are disregarded.

Converter

In HOMER, a converter is a device that transforms electricity from DC to AC (inversion) or from AC to DC (rectification). As described by Lambert *et al.* (2006), the converter size refers to the inverter capacity, this is, the maximum amount of AC power the equipment can deliver by inverting DC power. The rectifier capacity, which is the maximum amount of DC power the equipment can deliver by rectifying AC power, is expressed in HOMER as a percentage of the inverter capacity. HOMER assumes the efficiency of the converter device remains constant, and its capacity as inverter or rectifier can be kept continuous as long as necessary.

Based on the procedures described by Canales and Beluco (2014), the method explained in this paper requires the following conditions and considerations for the converter, in order to allow modeling a hydropower plant with reservoir in HOMER:

1. The inverter efficiency must be 100%. All losses must have been already included in the hydro inputs.
2. The rectifier capacity relative to inverter must be zero. By doing so, the excess electricity from the hydro would be the only source for refilling the reservoir, considering, as mentioned before, each cubic meter of water, both through the turbines as in the reservoir, represents the same amount of energy in terms of kilowatt-hours (kW·h).
3. The inverter must be able to operate in parallel with another AC power source.
4. The maximum converter size to consider must match the maximum power that could be provided by the hydropower plant.

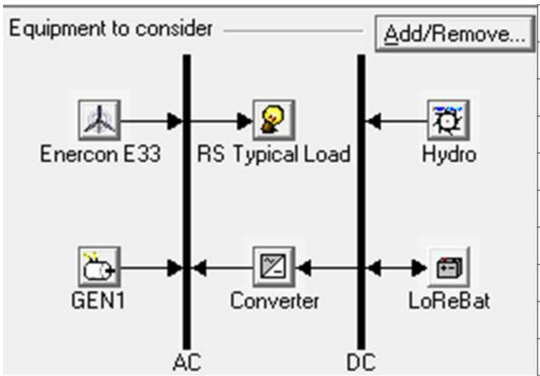
AN EXAMPLE USING DATA FROM RIO GRANDE DO SUL, BRAZIL

To illustrate and validate the method previously explained in this document, this section presents an example created from data related to Rio Grande do Sul, a southern state of Brazil. Initially, the power system used as case study is described, along with the corresponding literature sources for each component, and then, the results of two different test Scenarios are presented and discussed.

Description of the power system

System configuration

Simulating the operation and determining the best long-term configuration of a power system are two fundamental capacities of HOMER. The optimization algorithm in HOMER looks for the system configuration that minimizes the total net present cost. For the example presented in this paper, the following options were considered to serve an AC load: a hydropower plant with reservoir, a set of AC wind power turbines and an AC diesel generator. The AC load was created from information related to Rio Grande do Sul, and it was scaled to 4,000 kW·h/d and 10,000 kW·h/d to validate the model under two different demand conditions. Figure 1 shows the schematic diagram of the system and its corresponding search space, comprising 224 system configurations. The information related to cost per installed kilowatt was taken from Braciani (2011), using US$1 = R$2 as currency exchange rate.



Hydro (kW)	Battery (Quantity)	Generator (kW)	Enercon E-48 (Quantity)
0	0	0	0
394	1	50	1
		100	2
Converter		200	3
(kW)		400	4
408.25		600	5
		800	6
		1000	

Figure 1. Schematic diagram and search space of the system

Hydro installation and resource

The hydropower turbine was created based on information related to the lower reservoir of "System 2" or "Encantado-Forqueta" proposed by Beluco (2012). Considering that the turbines are to be located at the base of the dam (at elevation 200 m), the available head was chosen to be 63 m. The overall efficiency was assumed to be 85%, including conversion and pipe head losses. Figure 2 displays the flooded area of the reservoir and the basin above the dam. This figure was adapted from a small region (~80km²) of the Maquiné map sheet (SH.22-X-C-V-2), scale 1:50000, made by the Brazilian Army's Geographic Service Directorate (*Diretoria de Serviço Geográfico – DSG*, 1979).

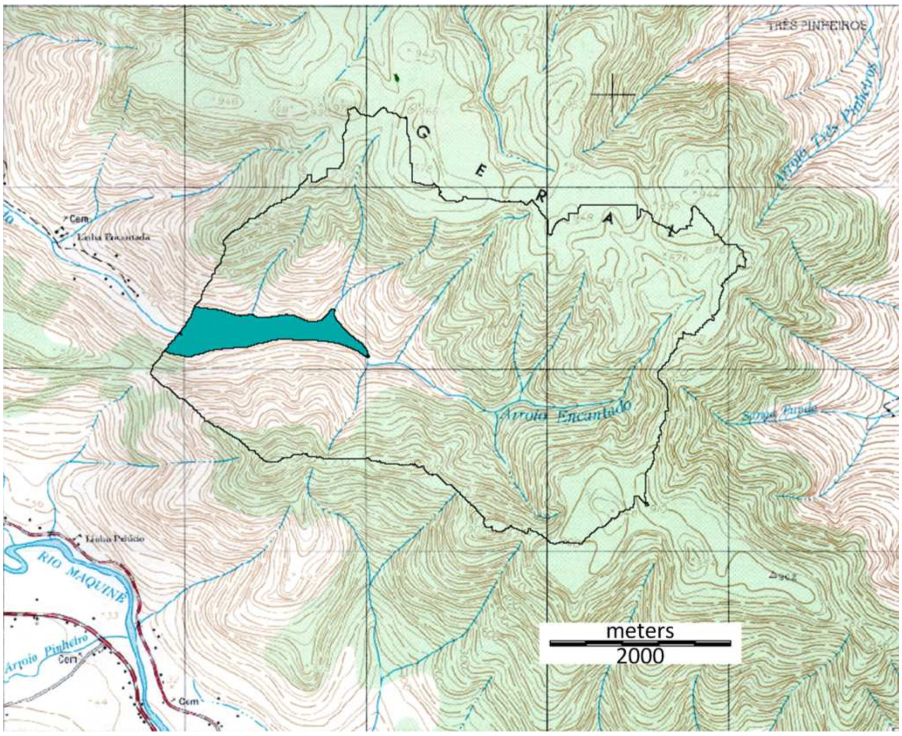


Figure 2. Flooded area and basin above the reservoir (Adapted from DSG, 1979)

To estimate the average stream flow available to the turbines each month, the discharge data series for the Encantado river were obtained from the website of the National Water Agency (Agência Nacional de Águas) of Brazil (http://hidroweb.ana.gov.br/, Station: 86720000). The watershed area above the gauging Station is 19,200 km², and above the dam of the lower reservoir is approximately 17.44 km². As a simplification, the proportion between these areas (0.0908%) was used to determine the monthly average flow for the watershed above the dam, as shown by the stacked column graph in Figure 3, and the annual average flow was calculated to be 0.508 m³/s. Based on the Tennant method described by Benetti *et al.* (2003), 10% of this annual average was selected as the instream or residual flow. After subtracting this residual flow, the top column with dashed line contour in Figure 3 shows the stream flow available to the turbines each month, for the system in consideration.

Taking the average flow for the month of May as example (Q = 0.4417 m³/s), the average power available to the hydro installation would be P_{hyd} = 232 kW. Correspondingly, during one hour, the average amount of energy available in the run-of-river would equal to 232 kW·h. Hence, a yield 0.1459 kW·h/m³ is obtained by dividing this energy by the volume of 1590 m³ also discharged during one hour.

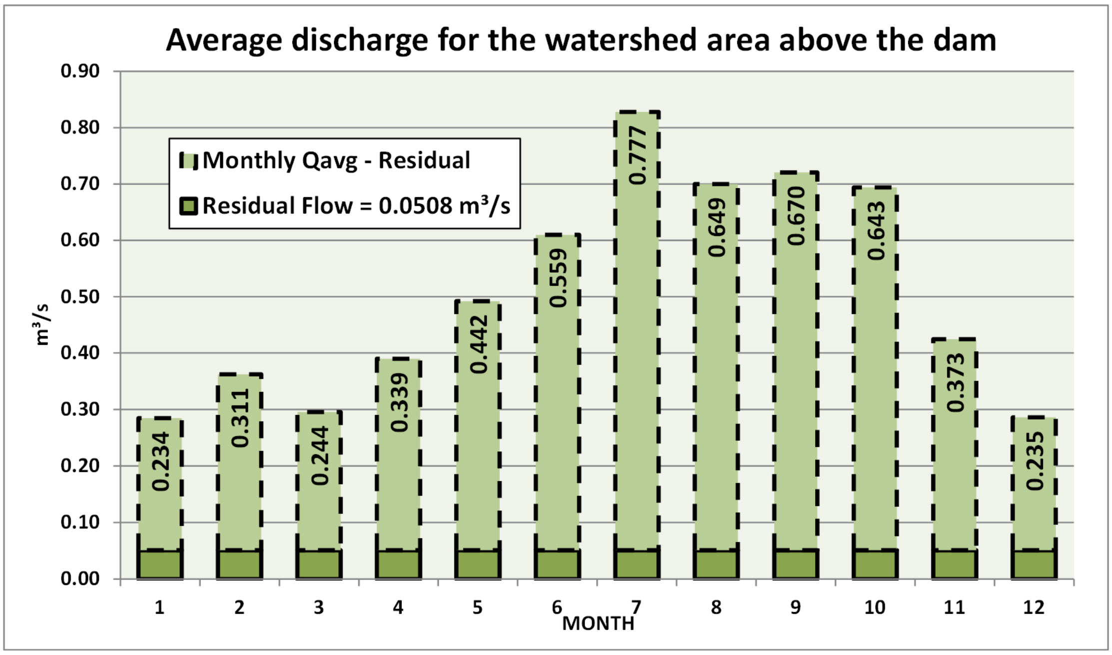


Figure 3. Average discharge for the watershed area above the dam

In HOMER, the design flow rate of the hydro turbine was set at 0.75 m³/s ± 70%, with the purpose of encompassing the whole range of available stream flows given in Figure 3, as suggested in the method described in this paper. Therefore the chosen nominal power for the hydro installation is 394 kW.

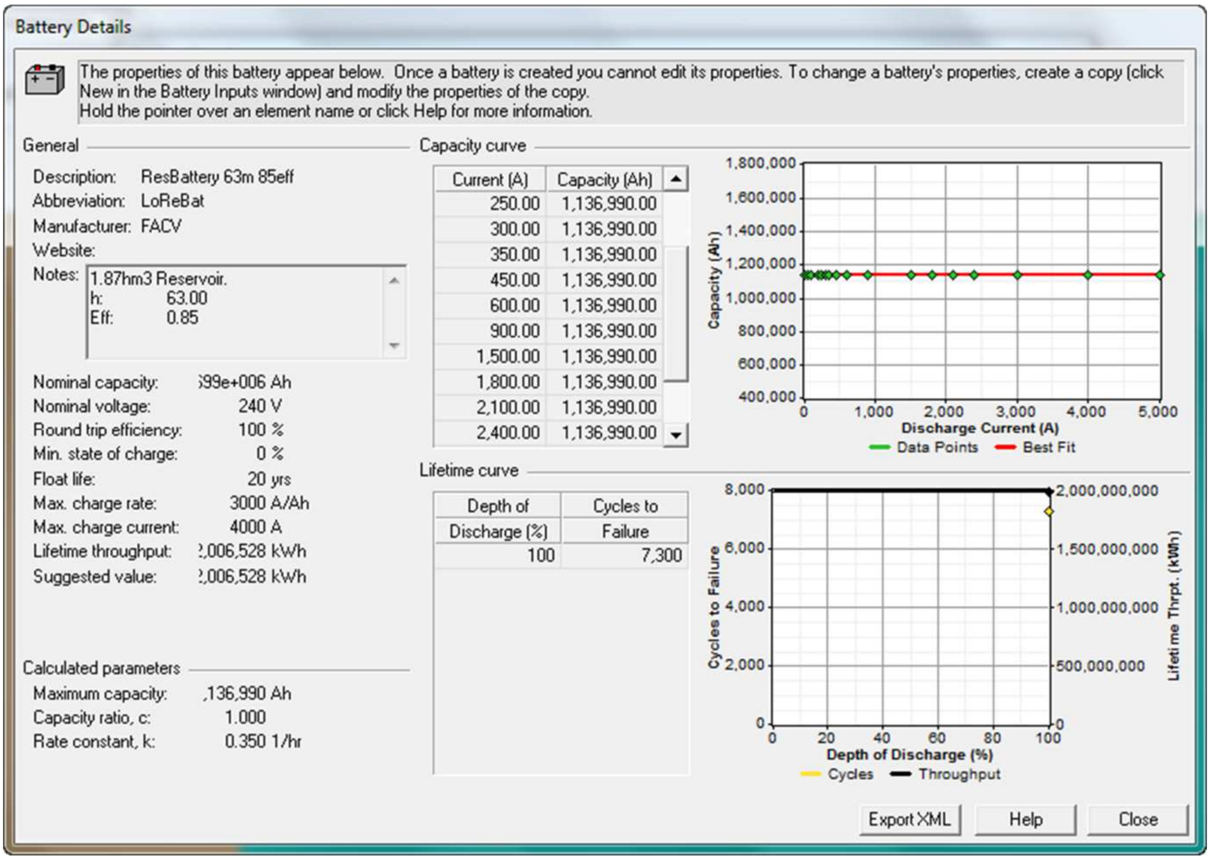
According to Braciani (2011), the average cost per installed kilowatt of hydropower with reservoir in Brazil is around US$1324/kW, with approximately 45% of this cost corresponding to the civil works. Then, by assuming 60% of the cost related to the hydro installation (pipes, electromechanical equipment, powerhouse, etc.) and 40% for the reservoir (dam and additional structures), the cost per installed kilowatt of the hydro (not including the reservoir) was set at US$794.4/kW.

Battery representing the reservoir

For this work, and based on Beluco (2012), it was assumed the active volume of the reservoir (*Vol*) as that contained between elevations 263m and 260m, estimated to be 1,870,000 m³. The total volume is 17,840,000 m³, and from the estimated average flow, it would take around 15 months to fill. By selecting 240 V as reference voltage, and replacing the known variables in equations (2) and (3), a total stored energy E_S = 272,878 kW·h and a capacity C_B = 1,136,990 A·h are found. As it can also be observed, dividing the active volume by the stored energy results in the same yield of 0.1459 kW·h/m³ found for the hydro installation.

The maximum charge current was defined as 4000 A, and the maximum charge rate as 3000 A/A·h. From equation (4), with $V = 240$ V and $P_{bat} = P_{hyd}(Q = 0.777\ \text{m}^3/\text{s}) = 408.25$ kW, the proportional charge current is $I = 1701$ A, and therefore, the maximum charge is at least proportional to the maximum stream flow expected. Once all these parameters are found and verified, the battery equivalent to the reservoir is created, as shown in Figure 4.

As mentioned before, by assuming that 40% of the US$1324/kW reported by Braciani (2011) corresponds to the construction of the reservoir, and taking as reference the nominal capacity of 394 kW, the cost of the reservoir was estimated to be US$208,660.



Battery Details

The properties of this battery appear below. Once a battery is created you cannot edit its properties. To change a battery's properties, create a copy (click New in the Battery Inputs window) and modify the properties of the copy.
Hold the pointer over an element name or click Help for more information.

General

Description: ResBattery 63m 85eff
Abbreviation: LoReBat
Manufacturer: FACV
Website:
Notes: 1.87hm3 Reservoir.
h: 63.00
Eff: 0.85

Nominal capacity: ;99e+006 Ah
Nominal voltage: 240 V
Round trip efficiency: 100 %
Min. state of charge: 0 %
Float life: 20 yrs
Max. charge rate: 3000 A/Ah
Max. charge current: 4000 A
Lifetime throughput: ;006,528 kWh
Suggested value: ;006,528 kWh

Calculated parameters

Maximum capacity: ,136,990 Ah
Capacity ratio, c: 1.000
Rate constant, k: 0.350 1/hr

Capacity curve

Current (A)	Capacity (Ah)
250.00	1,136,990.00
300.00	1,136,990.00
350.00	1,136,990.00
450.00	1,136,990.00
600.00	1,136,990.00
900.00	1,136,990.00
1,500.00	1,136,990.00
1,800.00	1,136,990.00
2,100.00	1,136,990.00
2,400.00	1,136,990.00

Lifetime curve

Depth of Discharge (%)	Cycles to Failure
100	7,300

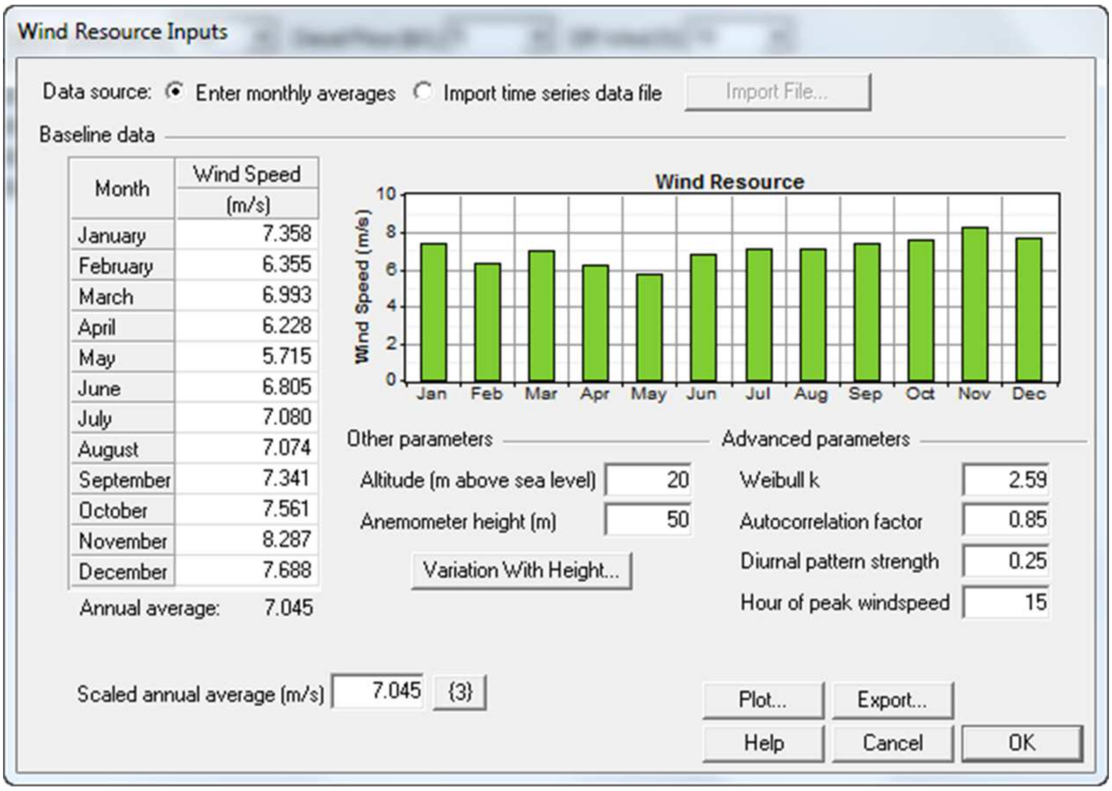
Figure 4. Representation of the reservoir as an equivalent battery

Wind turbine and resource

Because of the available wind resource, combined with the size of the loads and hydropower installation in analysis, the ENERCON E-48 was selected as AC wind turbine option for this model. The rated power of this equipment is 800 kW. The information related to this turbine was extracted from the ENERCON product overview, available at the company website (http://www.enercon.de/en-en/88.htm) and consulted on September 2014.

The location of the reservoir is approximately 25 km far from the coast of Rio Grande do Sul. Because of this, the wind resource for this area is considered to be the same as in Silveira (2011), measured in Mostardas, a coastal municipality in Rio Grande do Sul. The anemometer was placed at 50 m above ground, the same as the hub height used in the HOMER model for this example. The average annual Weibull parameter *k* found by the author was 2.588, with the hour of peak wind speed at 15 hours. Figure 5 shows the wind resource inputs in HOMER for this example.

Based on Braciani (2011), the average cost per installed kilowatt in a wind farm in Brazil is around US$2,156.50/kW. By using this value, the capital cost of each E-48 turbine was set at US$1,725,200 in HOMER.



Data source: ● Enter monthly averages ○ Import time series data file

Month	Wind Speed (m/s)
January	7.358
February	6.355
March	6.993
April	6.228
May	5.715
June	6.805
July	7.080
August	7.074
September	7.341
October	7.561
November	8.287
December	7.688

Annual average: 7.045

Altitude (m above sea level) 20

Anemometer height (m) 50

Weibull k 2.59

Autocorrelation factor 0.85

Diurnal pattern strength 0.25

Hour of peak windspeed 15

Scaled annual average (m/s) 7.045 {3}

Figure 5. Wind resource inputs in HOMER for this example

Converter

As previously explained in this document, the converter has 100% inverter efficiency, and 0% rectifier capacity relative to the inverter. The inverter can operate simultaneously with an AC generator. For this method, the importance of this device is that it represents and controls the hydropower installed capacity. For this paper, the assumed size of this component corresponds to $P_{hyd}(Q = 0.777 \text{ m}^3/\text{s}) = 408.25$ kW. Because it was not considered to represent a specific component of the system, the cost of this converter was set at US$500 in HOMER.

Generator

An AC diesel generator with HOMER's default settings was considered as one of the options to serve the load of the example. To promote the use of renewable energy sources, the price of diesel fuel was set at US$5/l. Several generator sizes were considered, as reported in Figure 1, with the minimum load ratio set at 10%. No cost penalties for emissions were assigned in this example. According to Braciani (2011), the average cost per installed kilowatt in a thermoelectric plant in Brazil is around US$1,073.50/kW.

Load

Two sources were used for creating the AC load profile for this example; both containing data related to Porto Alegre, capital city of Rio Grande do Sul, used as baseline. For non-touristic cities of the state, the demand behavior along the seasons is likely to be similar.

Based on the total monthly load consumption in Porto Alegre for the years 1997 and 1998, reported by Hansen (2000), the monthly averages and percent of the weighted average are presented in Table 1.

Table 1. Average and percent of weighted average for load consumption in Porto Alegre 1997-1998

Month	Days	1997 (kW·h/d)	1998 (kW·h/d)	1997-98 Avg. (kW·h/d)	% of weighted average
January	31	3,331,354	3,343,598	3,337,476	109.8%
February	28	3,176,327	3,086,213	3,131,270	103.1%
March	31	2,601,956	2,875,849	2,738,902	90.1%
April	30	3,032,598	2,993,063	3,012,830	99.2%
May	31	2,876,453	3,132,852	3,004,652	98.9%
June	30	2,987,283	3,026,442	3,006,863	99.0%
July	31	3,230,438	3,257,436	3,243,937	106.8%
August	31	3,055,956	3,121,659	3,088,807	101.7%
September	30	3,067,164	3,094,546	3,080,855	101.4%
October	31	2,910,074	2,983,794	2,946,934	97.0%
November	30	3,017,509	2,991,772	3,004,640	98.9%
December	31	2,787,781	2,950,112	2,868,947	94.4%
Average	30.42	3,006,241	3,071,445	3,038,221[a]	100.0%
Maximum	31	3,331,354	3,343,598	3,337,476	109.8%
Minimum	28	2,601,956	2,875,849	2,738,902	90.1%

[a] Weighted average, considering the days of each month.

To create the daily load profile for this example, it was used information available at Rahde and Kaehler (2000). In their work, they obtained the typical daily load curve for the residential customer (151 – 300 kW·h/month) in Porto Alegre. The hourly values were converted in order to represent the loads in terms of percentage of the total daily load, as shown in Figure 6.

The information given in Table 1 and Figure 6 was combined to create a file, used as data source by HOMER, containing the 8,760 lines representing the average electric demand (in kW) for each hour of the year. The average baseline demand was set at 100 kW·h/d. As previously mentioned, this baseline was scaled to 4,000 kW·h/d and 10,000 kW·h/d, in order to be used as the two scenarios for validating the method presented in this paper.

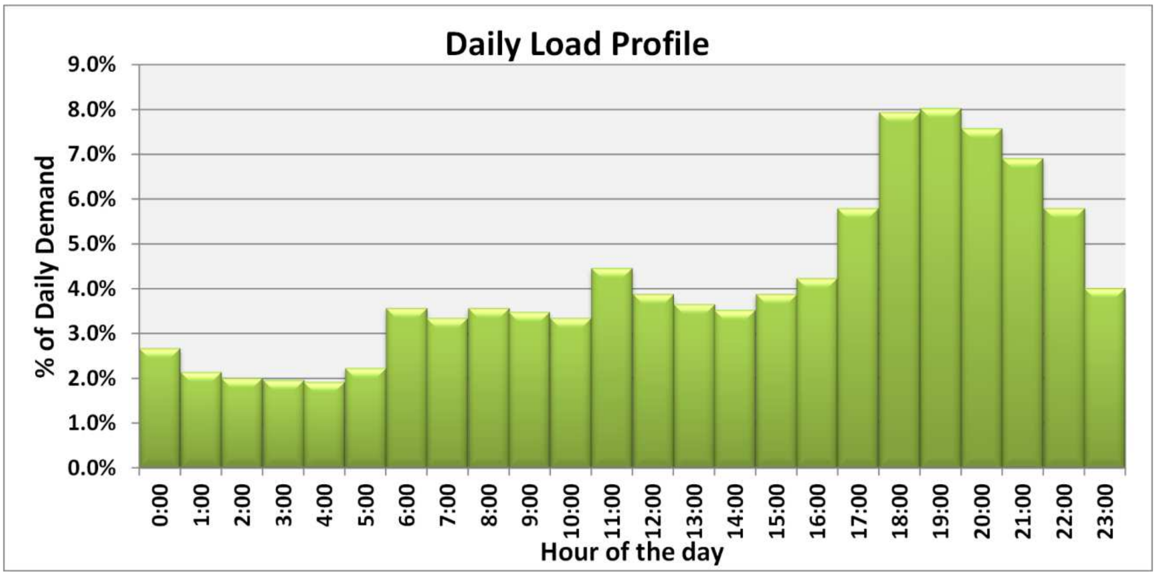


Figure 6. Hourly load profile, as a percentage of the total daily load

Additional considerations

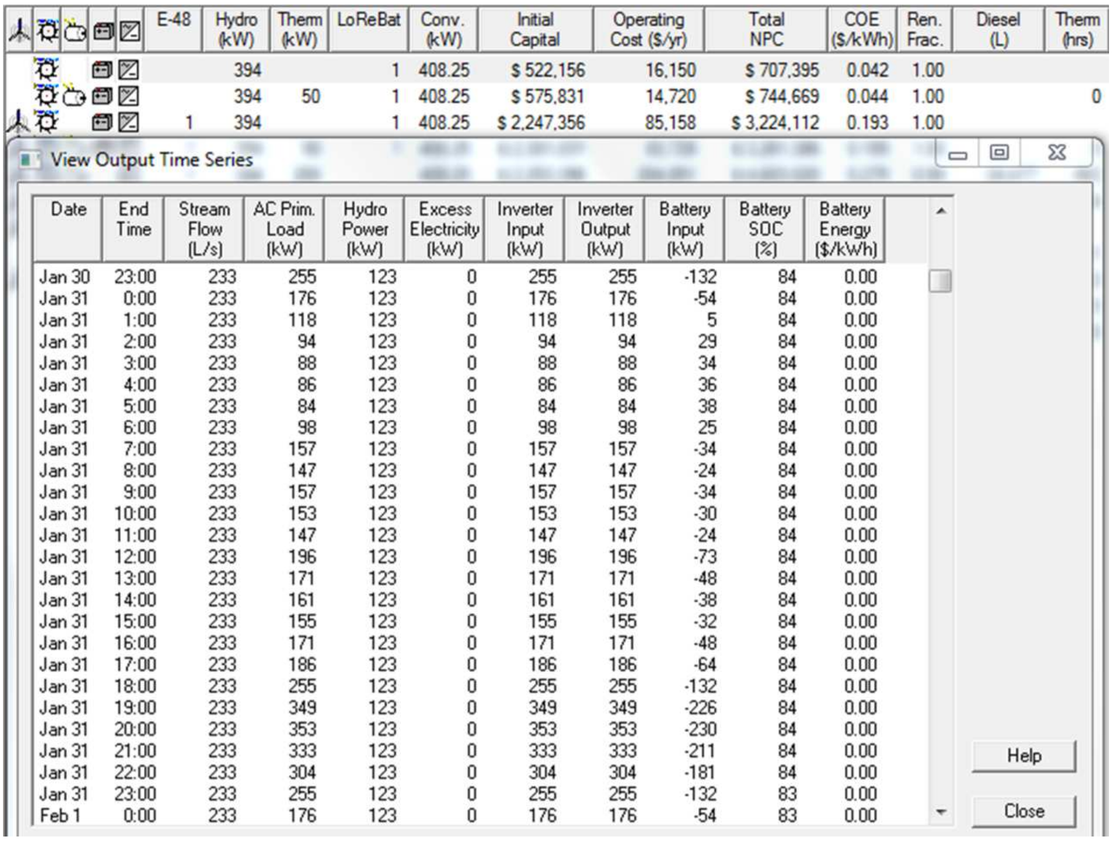
For the example presented in this document, besides the information and parameters described before, some other considerations and assumptions were made for the power system modeled in HOMER.

For the operating reserve, the 10% HOMER default value is used, meaning that the system must operate with enough spare capacity to serve an abrupt 10% increase in the load. As for the wind power operating reserve, this was set at 25%, based on the fact that the system would not need to rely on this type of renewable energy as its main source. The maximum allowable capacity shortage was set at zero and the dispatch policy is the load-following strategy.

The project and equipment lifetime was set at 20 years, with an annual real interest rate of 6%. Based on Jiandong *et al*. (1997), the annual operating and maintenance cost (O&M) for the hydropower installation and the battery representing the reservoir was set as 3% of the capital cost. For the wind turbines, it was adopted an O&M of 4%, a conservative estimate based on Lemming *et al.* (2009). The O&M for the AC diesel generator was set at US$0.01/kW per hour.

Scenario 1: Scaled annual average primary load of 4,000 kW·h/d

The HOMER optimization results for a system with a scaled annual average primary load of 4,000 kW·h/d indicate that the best system configuration, for such demand, includes the hydro turbine with reservoir as the only components required to serve this load. Figure 7 shows a screen capture of the output for a 24h period in Scenario 1, for the aforementioned configuration and at the month with the highest daily demand.



E-48	Hydro (kW)	Therm (kW)	LoReBat	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Therm (hrs)
	394		1	408.25	$ 522,156	16,150	$ 707,395	0.042	1.00		
	394	50	1	408.25	$ 575,831	14,720	$ 744,669	0.044	1.00		0
1	394		1	408.25	$ 2,247,356	85,158	$ 3,224,112	0.193	1.00		

View Output Time Series

Date	End Time	Stream Flow (L/s)	AC Prim. Load (kW)	Hydro Power (kW)	Excess Electricity (kW)	Inverter Input (kW)	Inverter Output (kW)	Battery Input (kW)	Battery SOC (%)	Battery Energy ($/kWh)
Jan 30	23:00	233	255	123	0	255	255	-132	84	0.00
Jan 31	0:00	233	176	123	0	176	176	-54	84	0.00
Jan 31	1:00	233	118	123	0	118	118	5	84	0.00
Jan 31	2:00	233	94	123	0	94	94	29	84	0.00
Jan 31	3:00	233	88	123	0	88	88	34	84	0.00
Jan 31	4:00	233	86	123	0	86	86	36	84	0.00
Jan 31	5:00	233	84	123	0	84	84	38	84	0.00
Jan 31	6:00	233	98	123	0	98	98	25	84	0.00
Jan 31	7:00	233	157	123	0	157	157	-34	84	0.00
Jan 31	8:00	233	147	123	0	147	147	-24	84	0.00
Jan 31	9:00	233	157	123	0	157	157	-34	84	0.00
Jan 31	10:00	233	153	123	0	153	153	-30	84	0.00
Jan 31	11:00	233	147	123	0	147	147	-24	84	0.00
Jan 31	12:00	233	196	123	0	196	196	-73	84	0.00
Jan 31	13:00	233	171	123	0	171	171	-48	84	0.00
Jan 31	14:00	233	161	123	0	161	161	-38	84	0.00
Jan 31	15:00	233	155	123	0	155	155	-32	84	0.00
Jan 31	16:00	233	171	123	0	171	171	-48	84	0.00
Jan 31	17:00	233	186	123	0	186	186	-64	84	0.00
Jan 31	18:00	233	255	123	0	255	255	-132	84	0.00
Jan 31	19:00	233	349	123	0	349	349	-226	84	0.00
Jan 31	20:00	233	353	123	0	353	353	-230	84	0.00
Jan 31	21:00	233	333	123	0	333	333	-211	84	0.00
Jan 31	22:00	233	304	123	0	304	304	-181	84	0.00
Jan 31	23:00	233	255	123	0	255	255	-132	83	0.00
Feb 1	0:00	233	176	123	0	176	176	-54	83	0.00

Figure 7. Output time series for a 24 h period in Scenario 1 – Scaled annual average primary load of 4,000 kW·h/d

Based on the information presented in Figure 7 and the complete output and results for the 8760 hours of the year, the following observations can be made about Scenario 1:

- 100% of the total load is served by the hydropower plant with reservoir, with an amount of excess electricity of 31.8% during the year.
- If the load is less than the energy produced by the hydro and the reservoir is not full (Battery SOC – state of charge – column < 100%), the hydropower excess is used to refill the reservoir. This behavior is represented by the positive values in the Battery Input column in Figure 7.
- If the load is more than the hydropower produced, the reservoir supplies the rest of the energy required to serve the load. This behavior is characterized by the negative values in the Battery Input column in Figure 7. The value in the inverter output column, which is the power delivered by the hydropower plant with reservoir to the system, is the sum of the hydropower served by the run-of-river installation and the power supplied by the battery representing the reservoir.
- For this Scenario, the total energy output of the battery is 174,566 kW·h/year.
- For additional validation of the method, some useful information can be obtained from the complete output time series for this scenario, as summarized in Table 2. The energy and water balance illustrates the equivalence between the reservoir and the battery, as exemplified by the correspondence between the values of lines [8] and [9] and that of lines [10] and [13].

Table 2. Output summary of the best option for the two Scenarios.

	Description	Units	Scenario 1	Scenario 2	Additional notes
[1]	Volume from streamflow	m^3	14,412,182.00	14,412,182.00	3.6 × Total sum of stream flow column
[2]	Energy from run-of-river hydro	kW·h	2,103,091.00	2,103,091.00	Total sum of Hydro Power column
[3]	Energy from wind power	kW·h	-	4,426,554.00	Total sum of E-48 Power column
[4]	Energy from diesel generator	kW·h	-	201,810.00	Total sum of Therm Power column
[5]	Excess electricity	kW·h	668,807.00	3,082,482.00	Total sum of Excess Electricity column
[6]	Effective energy	kW·h	1,434,284.00	3,648,973.00	[2]+[3]+[4]-[5]
[7]	Total AC Load	kW·h	1,460,001.00	3,650,025.00	Total sum of AC Prim. Load column
[8]	Battery must supply	kW·h	25,717.00	1,052.00	[7]-[6] After 8760 hours
[9]	Energy from battery	kW·h	25,736.00	1,073.00	(-1) × Total sum of battery input column
[10]	Final battery SOC	%	90.57%	99.61%	After 8760 hours
[11]	Final battery SOC	kW·h	247,145.60	271,813.78	[10] × E_S After 8760 hours
[12]	Reservoir must supply	m^3	176,264.56	7,210.42	[8] / 0.1459 kW·h/m^3
[13]	Final active volume in the reservoir	%	90.57%	99.61%	(*Vol* – [12]) / *Vol*

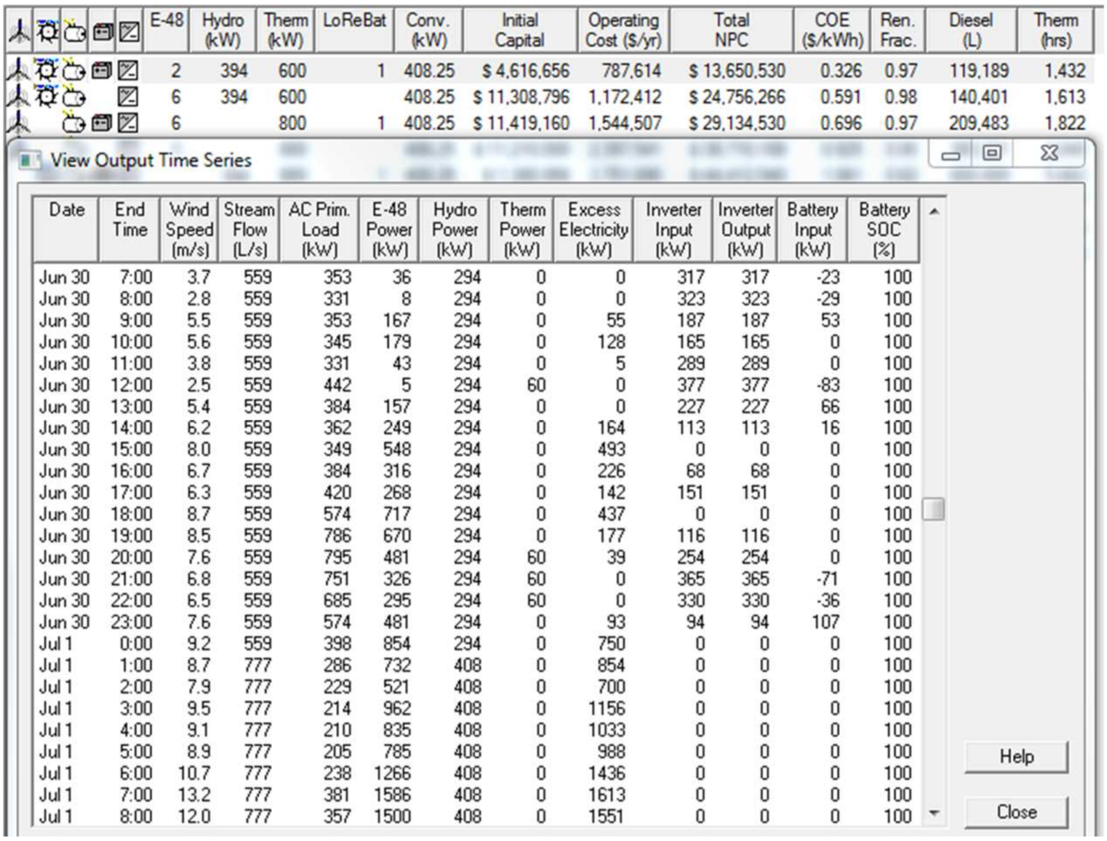
Scenario 2: Scaled annual average primary load of 10,000 kW·h/d

For Scenario 2, with a scaled annual average primary load of 10,000 kW·h/d, the HOMER optimization results indicate that the best system configuration to serve this load comprises: the hydro turbine with reservoir, two E-48 wind turbines and a 600 kW diesel generator. Figure 8 presents a screen capture of the output for a 24h period in Scenario 2, for the previously described configuration. Figure 9, showing the simulation results for electricity production in Scenario 2, it is also provided in order to facilitate a further understanding of the obtained results.

Based on the information presented in Figure 8, Figure 9 and the complete output and results for the 8760 hours of the year, some observations can be made about Scenario 2:

- 97% of the whole electrical production would come from renewable sources. This includes the energy supplied by the battery, which was charged by the hydropower excess. For Scenario 2, the amount of excess electricity is 45.8% during the year.
- The operating considerations of the battery representing the reservoir, related to its refill and its energy output, are the same as previously explained for Scenario 1.
- For this Scenario, the total energy output of the battery is 274,049 kW·h/year.

- As it can be observed from the inverter output column in Figure 8, the maximum power output from the hydropower plant with reservoir corresponds to the specified converter size of 408.25kW.
- The wind turbine capacity factor for this scenario is 31.6%. This value reported by HOMER includes the excess electricity.
- The AC diesel generator is activated only when the renewable energy output is not able to serve the load.
- As it was for Scenario 1, the output summary in Table 2 demonstrates the correspondence between the reservoir and its equivalent battery, even when multiple energy sources are included in the system configuration.



E-48	Hydro (kW)	Therm (kW)	LoReBat	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Therm (hrs)
2	394	600	1	408.25	$ 4,616,656	787,614	$ 13,650,530	0.326	0.97	119,189	1,432
6	394	600		408.25	$ 11,308,796	1,172,412	$ 24,756,266	0.591	0.98	140,401	1,613
6		800	1	408.25	$ 11,419,160	1,544,507	$ 29,134,530	0.696	0.97	209,483	1,822

Date	End Time	Wind Speed (m/s)	Stream Flow (L/s)	AC Prim. Load (kW)	E-48 Power (kW)	Hydro Power (kW)	Therm Power (kW)	Excess Electricity (kW)	Inverter Input (kW)	Inverter Output (kW)	Battery Input (kW)	Battery SOC (%)
Jun 30	7:00	3.7	559	353	36	294	0	0	317	317	-23	100
Jun 30	8:00	2.8	559	331	8	294	0	0	323	323	-29	100
Jun 30	9:00	5.5	559	353	167	294	0	55	187	187	53	100
Jun 30	10:00	5.6	559	345	179	294	0	128	165	165	0	100
Jun 30	11:00	3.8	559	331	43	294	0	5	289	289	0	100
Jun 30	12:00	2.5	559	442	5	294	60	0	377	377	-83	100
Jun 30	13:00	5.4	559	384	157	294	0	0	227	227	66	100
Jun 30	14:00	6.2	559	362	249	294	0	164	113	113	16	100
Jun 30	15:00	8.0	559	349	548	294	0	493	0	0	0	100
Jun 30	16:00	6.7	559	384	316	294	0	226	68	68	0	100
Jun 30	17:00	6.3	559	420	268	294	0	142	151	151	0	100
Jun 30	18:00	8.7	559	574	717	294	0	437	0	0	0	100
Jun 30	19:00	8.5	559	786	670	294	0	177	116	116	0	100
Jun 30	20:00	7.6	559	795	481	294	60	39	254	254	0	100
Jun 30	21:00	6.8	559	751	326	294	60	0	365	365	-71	100
Jun 30	22:00	6.5	559	685	295	294	60	0	330	330	-36	100
Jun 30	23:00	7.6	559	574	481	294	0	93	94	94	107	100
Jul 1	0:00	9.2	559	398	854	294	0	750	0	0	0	100
Jul 1	1:00	8.7	777	286	732	408	0	854	0	0	0	100
Jul 1	2:00	7.9	777	229	521	408	0	700	0	0	0	100
Jul 1	3:00	9.5	777	214	962	408	0	1156	0	0	0	100
Jul 1	4:00	9.1	777	210	835	408	0	1033	0	0	0	100
Jul 1	5:00	8.9	777	205	785	408	0	988	0	0	0	100
Jul 1	6:00	10.7	777	238	1266	408	0	1436	0	0	0	100
Jul 1	7:00	13.2	777	381	1586	408	0	1613	0	0	0	100
Jul 1	8:00	12.0	777	357	1500	408	0	1551	0	0	0	100

Figure 8. Output time series for a 24 h period in Scenario 2 – Scaled annual average primary load of 10,000 kW·h/d

In HOMER, the COE is the average cost per kWh of useful electrical energy produced by the system. Even for the best system design of Scenario 2, the COE value calculated by HOMER is higher than those published by the Electric Energy National Agency (*Agência Nacional de Energia Elétrica* – ANEEL) of Brazil. According to ANEEL (2008), the COE in Brazil ranges from US$0.05/kWh (small hydro and biomass) to US$0.25/kWh (diesel). Besides the considerations made regarding the cost of the components, the main reasons causing this difference are: 1) The simplification of assuming 20 years as the project lifetime and of all its components; 2) The wind profile, with a maximum attainable capacity factor of 31.6% for the wind turbines. A more uniform wind profile and a more accurate lifetime of each component would reduce the COE values found by HOMER. For example, Jiandong *et* *al*. (1997) state that the lifetime of civil works (such as dams) in hydropower projects is estimated between 30 and 40 years.

Another factor affecting the COE value is the amount of excess electricity, which could be sold to another grid or used to supply power to deferrable loads, instead of rejecting it by leaving wind turbines offline or discharging water through the spillway. It is also important to mention that the large diesel generator required for back-up has an extremely low capacity factor (3.84%); therefore, other options could be considered for reducing the COE value: allowing some capacity shortage, assess grid extensions for electricity imports, evaluate other energy sources, etc. This economic aspect is usually the most critical point in feasibility studies related to hybrid power systems.


Simulation Results

System Architecture: 2 Enercon E-48
394 kW Hydro
600 kW GEN1
1 ResBattery 63m 85eff
408 kW Inverter
Load Following

Total NPC: $ 13,650,530
Levelized COE: $ 0.326/kWh
Operating Cost: $ 787,614/yr

Production	kWh/yr	%
Wind turbines	4,426,554	66
Hydro turbine	2,103,091	31
GEN1	201,810	3
Total	6,731,455	100

Consumption	kWh/yr	%
AC primary load	3,650,025	100
Total	3,650,025	100

Quantity	kWh/yr	%
Excess electricity	3,082,482	45.8
Unmet electric load	0.00822	0.0
Capacity shortage	0.00	0.0

Quantity	Value
Renewable fraction	0.970

Figure 9. Simulation results for electricity production in Scenario 2

CONCLUSIONS

A hydropower plant with reservoir is an interesting option to consider in hybrid power systems, because it helps dealing with the great seasonal variability and daily intermittence of other renewable energies, such as photovoltaic energy or wind power. This is achieved by scheduling and optimizing the electricity generation from the potential energy stored in the reservoir. According to Sinha and Chandel (2014), the HOMER optimization model is the most widely used software tool in research studies regarding hybrid power systems. Nevertheless, current releases of HOMER do not include the option of adding a reservoir to the hydropower plant, and it just considers run-of-river schemes. This could restrict HOMER from finding the best system configuration within a set of available technologies for electricity production, one of its strong points when compared to other software tools.

This paper described a method for modeling a hydropower plant with reservoir in HOMER, accomplishing this by making some modifications to the procedure explained by Canales and Beluco (2014), in which they modeled a pumped hydro in HOMER. To illustrate and validate the method explained in this document, it was presented an example with two different scenarios, based on data related to Rio Grande do Sul, Brazil. The results indicate that a direct correspondence can be established between the equivalent battery and the reservoir, indicating an adequate representation is possible in HOMER. The refill of the reservoir, its power output as a function of the flow rate, and the installed capacity of the turbines are also suitably represented.

The method detailed in this document can be applied in feasibility studies for a preliminary assessment of different configurations of hybrid power systems in HOMER. It is also useful to compare other energy storage options like battery banks or pumped hydropower.

For future works derived from this paper, some cautions to be considered are: 1) The gross head, which is the difference in elevation between head and tail water, may affect the power output, in this paper the 3 meter difference was not deemed of much importance; 2) The method assumes that the whole range of available stream flows can be used for hydropower production, if this condition were not allowed, the available stream flow or volume in the reservoir might be underestimated; 3) HOMER simulates the operation of the system for a 8760 hour (1 year) period, so the maximum depletion of the reservoir at the end of this period should be taken into account at the start of the following year.

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OPTIMIZATION OF AUTONOMOUS POWER SYSTEMS WITH HYDROPOWER RESERVOIRS AND INTERMITTENT RENEWABLE SOURCES

Fausto A. Canales[a], Alexandre Beluco[b], Carlos André B. Mendes

Instituto de Pesquisas Hidráulicas (IPH), Universidade Federal do Rio Grande do Sul (UFRGS),
Av. Bento Gonçalves, 9500 CEP: 91501-970 - Porto Alegre - RS - Brasil

ABSTRACT

Hydropower reservoirs (of conventional and pumped storage plants) provide dispatchable power and large-scale energy storage. They are a suitable technology in autonomous power systems with high levels of renewable generation, because of their capacity to buffer intermittencies and high variability of renewable energies such as wind and solar power. This paper presents a method to assess the optimal configuration of an autonomous hybrid power system that includes intermittent renewable energy sources and hydropower reservoirs. The method exploits the available features of the Legacy Version of HOMER (Hybrid Optimization Model for Electric Renewables), a widely used computer model that assists in the design of hybrid power systems. The case study of this paper was created from data related to Rio Grande do Sul, Brazil. The procedures explained could help in the definition of the best use of a site with hydropower potential. The method described in this work can also be used to estimate how much excess electricity can be recovered by means of pumped storage hydropower. The results show that the optimal design depends on many factors such as hydrological constraints, average load to serve and energy cost of each source.

Keywords: *hydropower; pumped storage hydropower; energy storage; renewable energy; optimization; HOMER software.*

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[a] E-mail: fausto.canales.v@gmail.com

[b] Author to whom correspondence should be addressed. E-mail: albeluco@iph.ufrgs.br Tel.:+55 51 33086407

I. INTRODUCTION

Besides environmental benefits, one of the main advantages of some renewable energy technologies (like solar and wind power projects) is their reduced construction time when compared to other power plants (like fossil fuel or hydropower). This enables them to provide a more accurate response to the load growth, while minimizing the financial risk that comes with borrowing millions of dollars to finance other types of plants for several years before they start generating their first kW of electricity (SOVACOOL, 2009). However, autonomous power systems with high levels of renewable generation require adequate measures to overcome the intermittency and stochastic nature associated to most of these energy sources, in order to keep the balance between energy supply and consumption. This balance is important to maintain the quality of the electricity supply by regulating the grid frequency and voltage. A combination of dispatchable technologies and energy storage is one of the most common methods to achieve this equilibrium (REIS, 2003).

Besides providing dispatchable power and operating reserve with short start-up times and lower costs, hydropower reservoirs (of conventional and pumped storage hydro) are the main option for large-scale electricity storage in the form of potential energy, enabling their future consumption when the load exceeds the generation capacity available from the renewable source (CHANG *et al.*, 2013). The generating capacity of conventional hydropower plants with reservoir is constrained by site specific features, such as available head, reservoir capacity and hydrological limitations (stream flow entering the reservoir, rainfall, seasonal weather conditions, additional reservoir uses, etc.). Hydropower plants with pumped storage capabilities partially overcome these issues, by recovering rejected (excess) energy from wind or solar farms to refill an upper reservoir, achieving a maximum exploitation of these intermittent renewable resources.

Pumped storage hydropower (PSH), based on the same principles of conventional hydro, is the most widely used large-scale electrical energy storage technology. According to the International Energy Agency (IEA, 2014), at least 140GW of large-scale energy storage are currently installed in electrical power grids around the world, with 99% of this capacity coming from PSH technologies, and the other 1% from a mix of batteries, compressed air energy storage (CAES), flywheels and hydrogen storage. Barnhart and Benson (2013) explain that storage is an attractive load-balancing technology because it increases reliability and flexibility of the power grid (especially in locations with ambitious climate-change policies), while at the same time it helps decreasing carbon emissions by reducing the transmission load and enabling spinning power plants to operate at optimum efficiency. Regarding energy storage through PSH, Glasnovic and Margeta (2011) mention that if site conditions are suitable, the smaller reservoirs and different possible configurations of the PSH plants allow building the different components of the hybrid power system close to energy consumers. This would significantly reduce energy losses due to transport, which could range from 8% to 15%.

During recent years, a number of papers have been published on the subject of size optimization of hybrid power systems including PSH to recover excess energy from intermittent sources, in order to serve the loads in isolated (stand-alone) or autonomous (independent, but able to connect to the grid) hybrid power systems. Some of them are the works on Greek islands written by Anagnostopoulos and Papantonis (2008), Kaldellis *et al.* (2010) or Kapsali and Kaldellis (2010). Glasnovic and Margeta (2011) and Glasnovic *et al.* (2011) explore the Concept-H, based exclusively on the use of renewable resources and predominant use of water reservoirs as energy storage. Among others, it is also possible to cite the publications by Castronuovo and Lopes (2004), Foley *et al.* (2015), Krajačić *et al.* (2011), Nyamdash *et al*. (2010) and Chang *et al*. (2013). All these papers involve using commercial software or writing specific computer models based on given sets of equations that must be carefully validated by the researcher.

Based on Canales and Beluco (2014), this paper presents a method to perform an assessment of the optimal design and to obtain the whole set of feasible configurations for an autonomous or isolated hybrid power system including intermittent renewable energy sources and hydropower reservoirs. The method takes advantage of the available features of the Legacy Version of HOMER (Hybrid Optimization Model for Electric Renewables), freely available at http://homerenergy.com/. The results of a case study created from data related to Rio Grande do Sul, Brazil, are presented and discussed to validate the method.

According to Sinha and Chandel (2014), and with thousands of users around the world, HOMER is the most widely used tool in research studies related to hybrid power systems, mainly due to its user-friendly interface and detailed documentation. HOMER is described by Georgilakis (2006) as a computer model that assists in the design of hybrid power systems, including several different power generation technologies for this purpose (photovoltaic modules, wind turbines, run-of-river hydropower, batteries, generators, etc.). HOMER is mainly an economical model dedicated to system selection and pre-sizing, which models the physical behavior and lifecycle cost of a power system. HOMER executes three main tasks:

1. Simulation: Performing energy balance calculations for each of the 8,760 hours in a year, HOMER estimates the cost and determines the feasibility of a system design. A complete and detailed output is produced for every feasible system configuration in the search space.
2. Optimization: After simulating all the possible system configurations, HOMER sorts the feasible projects according to the Net Present Cost (NPC).
3. Sensitivity analysis: Except for decision variables, most numerical input variables in HOMER can be sensitivity variables. By assigning more than one value to each input of interest, this capacity is useful to observe how the results could vary, either because the range of values is uncertain or because they represent a variety of applications.

As of today, a weakness of HOMER is that the model does not support some renewable technologies, among these, hydropower with reservoir and PSH. However, as explained by Canales and Beluco (2014), one effective way to overcome this shortcoming is to represent the reservoir as an equivalent battery, and this approach is used in this document. Future releases or custom versions of HOMER might include specific elements to model these components.

II. METHOD

The paper written by Canales and Beluco (2014) explained how to model PSH with HOMER, an extensively tested tool for assessing the best configuration and performance of hybrid power systems comprising renewable and non-renewable energy sources. With a few modifications, the method explained by them can also be used for modeling a conventional hydropower plant with reservoir.

Based on these techniques, and besides assessing the optimal system design, this paper describes how to use HOMER for estimating how much intermittent renewable energy (like wind or solar power) could be recovered by means of PSH. In addition to that, it allows comparing how a site with potential for both conventional and PSH could be better used in a hybrid power system. These two objectives are achieved by taking advantage of some important features of HOMER: the optimization module, its sensitivity analysis capabilities and the detailed output for a simulation period of 8760 hours.

It is worth mentioning that the procedures explained in this paper are not site specific, and they can be easily adapted to any other region of the world where the following information is available: (i) data regarding intermittent renewable sources, such as solar radiation or wind speed; (ii) generation cost and load information; (iii) a site suitable for the construction of hydropower reservoirs.

A. Pumped storage hydropower modeling

Hydropower reservoirs and batteries are able to store energy and supply it on demand. This analogy allows the user to create an equivalent battery in HOMER for modeling the reservoir. The software considers that the battery properties remain constant during its entire lifetime. According to Canales and Beluco (2014), the following equation describes the total stored energy E_S (in kW·h) in the active volume of a reservoir Vol (in m^3):

$$E_S = 9.81 \times \eta_{hyd} \times H \times Vol / 3600 \tag{1}$$

In Equation (1), H is the effective head (m) and η_{hyd} the efficiency in conversion in turbine mode (%).

Considering a battery with fixed voltage V and with capacity C_B (in Ampere·hours, A·h) independent of the discharge current, its stored energy is found by the expression:

$$E_S = V \times C_B / 1000 \tag{2}$$

The power delivered by the battery (in kW) is proportional to the discharge current I (in A), and is calculated by the formula:

$$P_{bat} = V \times I / 1000 \tag{3}$$

Based on the main features of the PHS site and assuming gross head H constant, Canales and Beluco (2014) explain that PSH can be modeled in HOMER through the following steps:

1. Select a reference voltage for the equivalent battery and find the capacity C_B (in A·h) of the equivalent battery, proportional to the reservoir volume. The battery must be the only component in the DC bus.
2. In HOMER, create an equivalent battery with the previously selected reference voltage and constant capacity found, 100% round trip efficiency and minimum state of charge 0%. The maximum charge current should be proportional to the time required to fill the reservoir.
3. Use the converter to represent the different options for the installed capacity of the hydropower plant. The conversion efficiency in both ways (pump and turbine mode) is controlled via this component.

Besides selecting the required installed capacity from the set of converter sizes to consider, this procedure can be modified to optimize the size of the reservoirs. To do so, a unitary battery is created based on the minimum active volume of the upper reservoir, and different volumes can be assessed by means of a battery bank with more batteries, representing multiples of the reference volume. The cost of the battery must reflect the combined cost of the upper and lower reservoirs.

The method assumes variable speed pump/turbine units. This technology uses asynchronous motor-generators that enable adjusting the pump/turbine rotation speed, regulating the amount of energy absorbed in pumping mode. According to Deane *et al.* (2010), this facilitates energy storage when the grid power levels available are low, and it also reduces the number of starts and stops of the equipment.

B. Hydropower plant with reservoir modeling

For each hour of the simulation, HOMER uses the following expression to calculate the power output of a hydro turbine:

$$P_{hyd} = \eta_{hyd} \times H \times \rho_{H2O} \times g \times Q \,/\, (1000W/kW) \tag{4}$$

In Equation (4), P_{hyd} is the power output of the hydro turbine (kW), ρ_{H2O} the density of water (1000kg/m³), g the gravitational acceleration (9.81m/s²) and Q is the flow rate through the turbine (m³/s).

With a few modifications, the method described for modeling PSH can be used also for hydropower with reservoir. The procedure requires three components:

1. *A DC hydropower turbine:* Along with the battery representing the reservoir, this is the only equipment assigned to the DC bus. All losses must be included in the efficiency value, to guarantee that each cubic meter of water, both through the turbines and in the reservoir, represents the same amount of energy. If residual flow is being considered, this should be subtracted before the HOMER input. The minimum and maximum flow ratios shall cover the full range of available stream flows. The HOMER Legacy version (used in this paper) can only consider a single size of hydropower system.

2. *A battery representing the reservoir:* The only other equipment on the DC bus. A reference voltage for the equivalent battery must be selected to find a C_B value proportional to the active storage volume of the reservoir. In the same way as in pumped hydropower modeling, the equivalent battery should have a round trip efficiency of 100% and minimum state of charge 0%, with a maximum charge current proportional to the maximum stream flow expected. Losses from withdrawal, evaporation or infiltration are disregarded.
3. *A converter:* The efficiency of the inverter must be 100% and all losses should have been already incorporated in the hydro inputs. By setting the rectifier capacity relative to inverter as zero, the excess electricity from the hydro becomes the only source for refilling the reservoir. Additionally, the inverter must be able to operate in parallel with another AC power source, and the maximum converter size must match the maximum power that could be produced by the hydropower plant.

C. Estimating the recovery capacity of rejected energy

As explained by Levine (2011), the process of pumping water up and its posterior release through the hydropower turbines is not 100% efficient in the energy return. A fraction of the energy used to pump the water cannot be reverted to electric energy by the turbines. This efficiency loss is a result of the rolling resistance and turbulence in the penstock and tail race, as well as consequence of efficiency losses in the electromechanical equipment.

When using pumped hydropower for energy storage, Kaldellis *et al.* (2010) explain that the absorption of rejected renewable energy usually grows with the increase of the upper reservoir volume and the nominal power of the hydro turbines. In a hybrid power system containing these elements, determining the optimum size of its components is a multi-parametric problem with hundreds, or thousands, of possible system configurations, and HOMER is able to evaluate the performance of each one in a single run, sorting them in terms of its NPC.

For each system configuration and sensibility analysis case, HOMER is able to provide a complete and detailed output of the system operation by making energy balance calculations for each of the 8,760 hours in a year, showing in columns each relevant element for this computation. By means of this feature is possible to estimate the time variation of the rejected power and the amount that can be recovered by means of energy storage through pumped hydropower, among other variables, as it will be presented on the section discussing the results of the case study of this paper.

The capacity factor (CF) is a measure that indicates the actual electricity delivered by a power plant relative to the maximum it could produce at continuous full power operation during the same time. For example, by considering the PSH system as the battery bank of a wind farm, the HOMER output allows estimating the electricity effectively delivered by the wind farm and its corresponding capacity factor through the following equation:

$$CF = \frac{Wind\ Energy\ Available + Turbines\ Energy - Pumps\ Energy - Excess}{8760 \times Wind\ Power\ Installed\ Capacity} \quad (5)$$

III. CASE STUDY PRESENTATION

This section describes the hypothetical autonomous or isolated system used as case study in this paper. The example was created from real data related to Rio Grande do Sul, a southern state of Brazil. It is important to mention that the wealth of water resources in Brazil allowed the construction of many big hydropower plants with huge reservoirs in the past decades. These plants are the core of the Brazilian National Interconnected Power System (*Sistema Interligado Nacional* – SIN), which demands a complex operation plan and a transmission grid of approximately 100,000km. About 90% of the total energy production of the SIN comes from hydropower (REIS, 2003). The region complementarity of hydrological and wind regimes, efficiency of the SIN and the abundance of resources are the main reasons why pumped storage hydropower is practically inexistent in Brazil. Environmental concerns related to flooding vast areas (mainly in the Amazonia) and air pollution, as well as incentives for diversifying the electricity generation mix might require the future use of PSH or other energy storage technologies in Brazil (GALHARDO, 2012).

Wind power is used as the intermittent renewable energy source for this case study. As with the majority of renewable technologies, grid planning analysis must take into consideration the fact that most of the time the generation of these plants is lower than the installed nominal power.

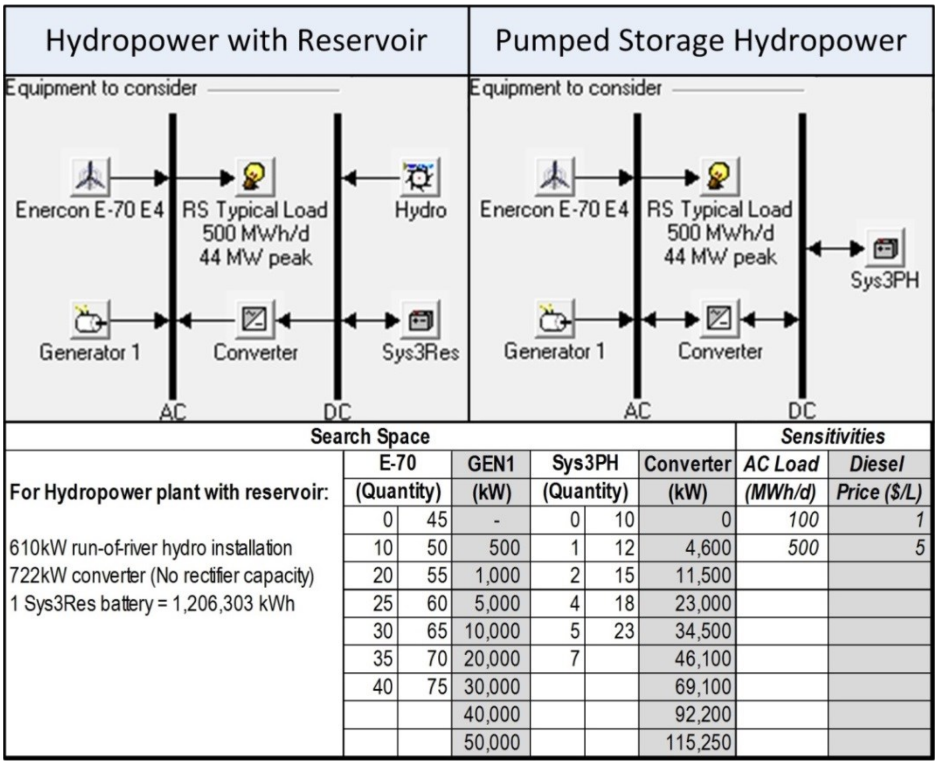
A. System configuration

HOMER simulates the system operation and is able to determine the best long-term configuration of a power system. Its optimization algorithm looks for the system configuration that minimizes the total Net Present Cost. For this case study, the following options were considered to serve an AC load:

- A set of AC wind power turbines.
- An AC diesel generator.
- One of two options: a hydropower plant with reservoir or a PSH plant.

For this paper, the AC load was created from information related to Rio Grande do Sul, and it was scaled to 100MW·h/d and 500MW·h/d, to validate the model under different demand conditions. Figure 1 displays the schematic diagram for both systems to consider and its corresponding search space.

To estimate the capital cost of these generating units, two main information sources were used: Pasquali (2006) and Braciani (2011). The currency exchange rate used is US$1 = R$2.



Search Space							*Sensitivities*	
For Hydropower plant with reservoir:	**E-70 (Quantity)**		**GEN1 (kW)**	**Sys3PH (Quantity)**		**Converter (kW)**	***AC Load (MWh/d)***	***Diesel Price ($/L)***
	0	45	-	0	10	0	*100*	*1*
610kW run-of-river hydro installation	10	50	500	1	12	4,600	*500*	*5*
722kW converter (No rectifier capacity)	20	55	1,000	2	15	11,500		
1 Sys3Res battery = 1,206,303 kWh	25	60	5,000	4	18	23,000		
	30	65	10,000	5	23	34,500		
	35	70	20,000	7		46,100		
	40	75	30,000			69,100		
			40,000			92,200		
			50,000			115,250		

Figure 1. Schematic diagrams and search space

B. Hydropower generation and resource

For this case study, only one of two options for hydropower generation could be used: a hydropower plant with reservoir or a PSH plant. The basic features and the stream flows used to estimate the power generation capacity are described in the following subsections.

1. Location and hydro resource

The representation of the hydropower projects for this case study was made according to the location described by Beluco (2012) for "System 3" or "*Linha Sete*". Figure 2 shows the basin contour for both reservoirs. This figure was adapted from a small region (~80km²) of the Barra de Ouro map sheet (SH.22-X-C-V-1), scale 1:50000, made by the Brazilian Army's Geographic Service Directorate (*Diretoria de Serviço Geográfico* – DSG, 1979).

To estimate the average monthly stream flow available, it was used a contiguous basin, assuming that it has the same hydrological characteristics of the one in which the system is located. The discharge data series for the Encantado river were obtained from the website of the National Water Agency (*Agência Nacional de Águas*) of Brazil (http://hidroweb.ana.gov.br/, Station: 86720000).

The watershed area above the gauging Station is 19,200km², above the upper reservoir dam is approximately 6.15km² and 18.5km² above the lower reservoir. Because of the small area above the upper dam, only the lower one is considered feasible for building a hydropower plant with reservoir. As a simplification, the proportion between these areas (0.0964%) was used to determine the monthly average flow for the watershed above the dam, as presented in Figure 3. The annual average flow was calculated to be 0.539m³/s.

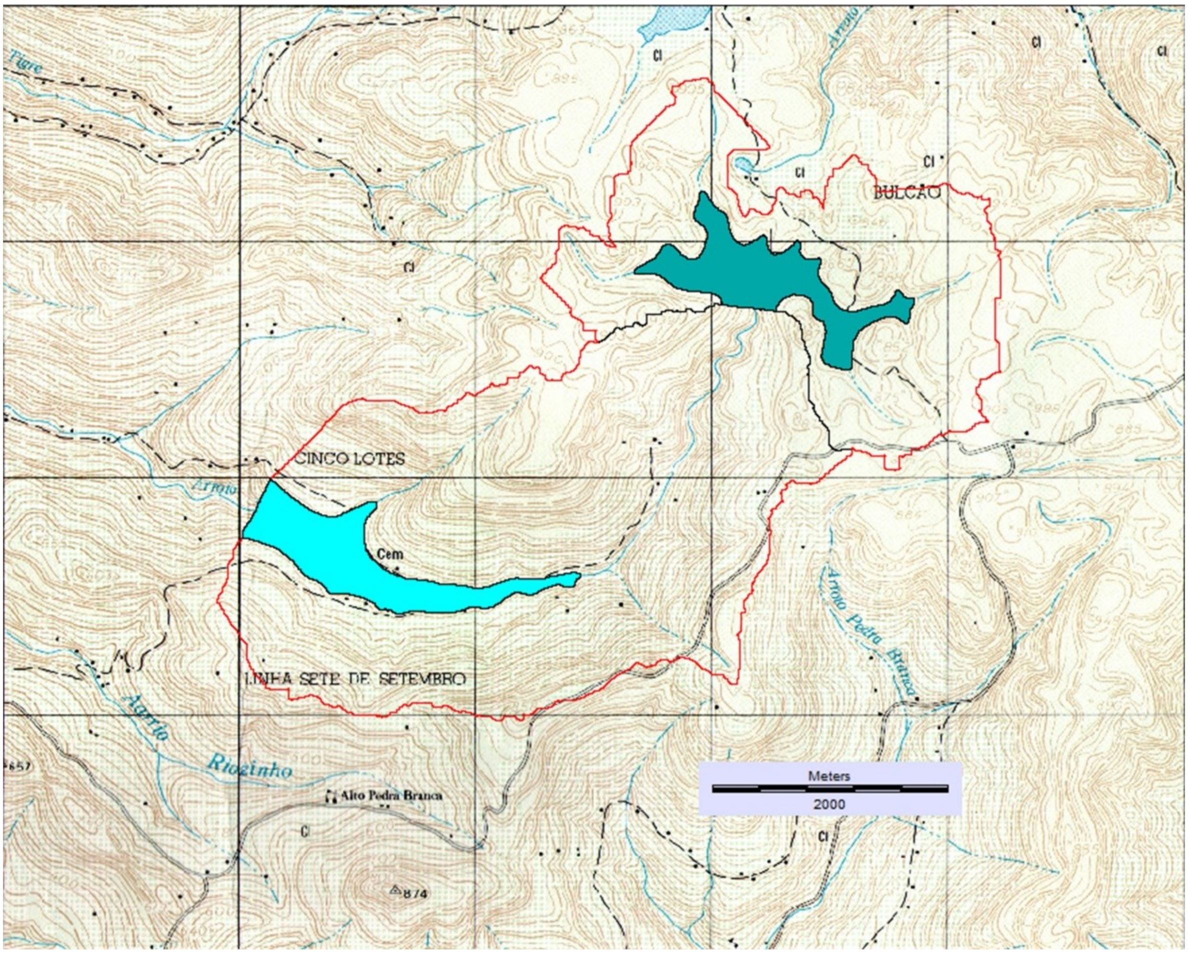


Figure 2. Basin contour for "System 3" or "*Linha Sete*" upper and lower reservoirs (adapted from DSG, 1979)

Based on the Tennant method described by Benetti *et al.* (2003), 10% of the annual average flow was adopted as the instream or residual flow. Once subtracted this residual flow, the top column with dashed line contour in Figure 3 shows the stream flow available to the turbines each month.

2. Representing the hydropower plant with reservoir

As previously explained in the method section, representing a hydropower plant with reservoir in HOMER requires three elements:

- A DC hydropower turbine: The design flow rate of the hydro turbine was set at 0.70m³/s ± 75%, which allows including the whole range of available stream flows given in Figure 3, as explained in the method section. The available head used is H = 105m, based on the assumption that the active volume (Vol) of the reservoir is that contained between elevations 360m and 350m, and the turbine is at elevation 250m. Consequently, the chosen nominal power for the hydro installation is 610kW. By dividing the average energy available in the run-of-river energy by the corresponding volume discharged during one hour, it yields 0.2432kW·h/m³. The overall efficiency was assumed to be η_{hyd} = 85%, including conversion and pipe head losses.

- *A battery representing the reservoir*: Based on the information at Beluco (2012), the *Vol* = 4,960,000m³. The total volume is 18,730,000m³, and it would take about 15 months to fill based on the estimated average flow. By selecting 10kV as reference voltage in equations (1) and (2), a total stored energy E_S = 1,206,303kW·h and a capacity C_B = 120,630A·h are found. It can also be observed that dividing the stored energy by the active volume results in the same yield of 0.2432kW·h/m³ found for the hydro installation. The maximum charge current was defined as 100A, and the maximum charge rate as 100A/A·h.
- *Converter:* This device represents the maximum power that could be produced by the hydropower plant. For this case study, the size of this component is the one that corresponds to P_{hyd}(Q = 0.825m³/s) = 722kW.

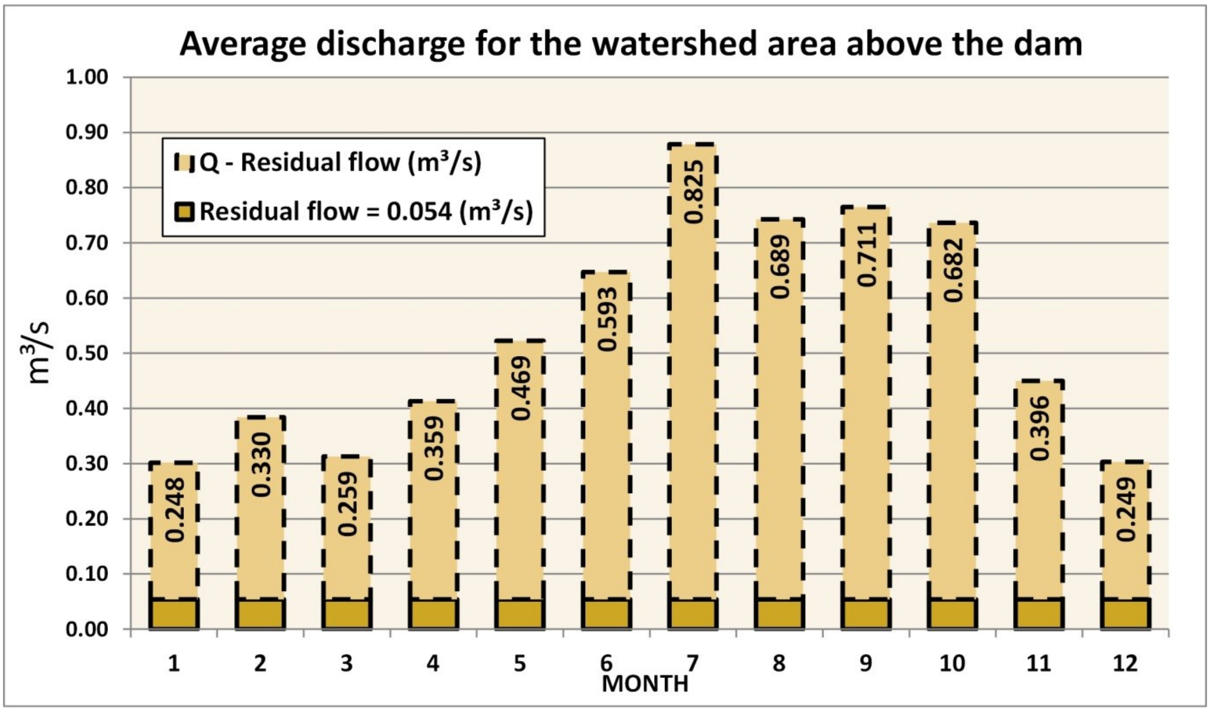


Figure 3. Average discharge for the watershed area above the lower reservoir dam

According to Braciani (2011), the average cost per installed kilowatt of hydropower with reservoir in Brazil is around US$1324/kW. Around 45% of this cost corresponds to the civil works. In this case study, the capital cost of the project was divided equally among the three HOMER components required for representing the hydropower plant with reservoir.

3. Representing pumped storage hydropower

The "System 3" described by Beluco (2012) is used as the PSH plant for this case study. The length of the pipes connecting both reservoirs was calculated as 4.5km, and the available head, taken as a fixed value, is the difference between the lower elevations of both dams. According to Canales and Beluco (2014), PSH plants can be modeled in HOMER as a combination of a battery bank and a converter. For this case study, the set of cost functions presented by Pasquali (2006) was used for estimating the PSH cost.

- *A battery bank:* The upper reservoir volume of 1,510,000m³, corresponding to elevation 740m in Beluco (2012), is used to create the unitary battery for this case study. For the unitary battery, using 10kV as the reference voltage in equations (1) and (2) produces E_S = 1,933,932kW·h and C_B = 193,393A·h. Dividing the stored energy in the upper reservoir by its volume results in 1.28kW·h/m³. The maximum charge current was defined as 15000A, and the maximum charge rate as 15000A/A·h. The length of each dam at different elevations, required for cost estimation, was assessed using GIS software. Depending on storage capacity, this case study evaluates several reservoir combinations, represented by the quantity of Sys3PH batteries to consider in the model, as shown in Figure 1. For this case study, Figure 4a shows the relationship between the dams costs and the storage capacity of the upper reservoir.
- *Converter:* This case study will consider several options for the installed capacity of the pumped hydropower plant represented in HOMER, as listed in Figure 1. The conversion efficiency for pumps (rectifier) and turbines (inverter) is set at 85% for both. Except for the dams, all the other PSH costs are included in the converter cost. Figure 4b shows the relationship between these costs and the installed capacity of the hydropower pumps/turbines for this example.

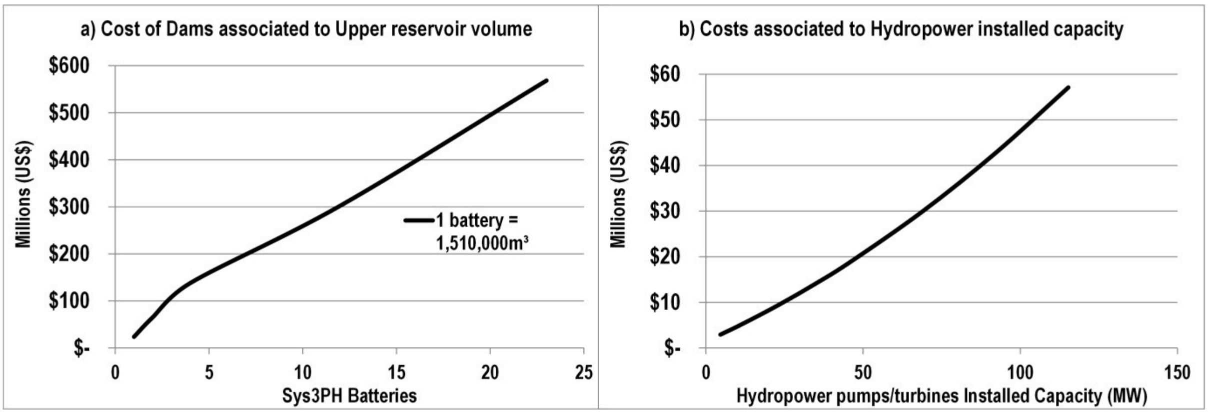


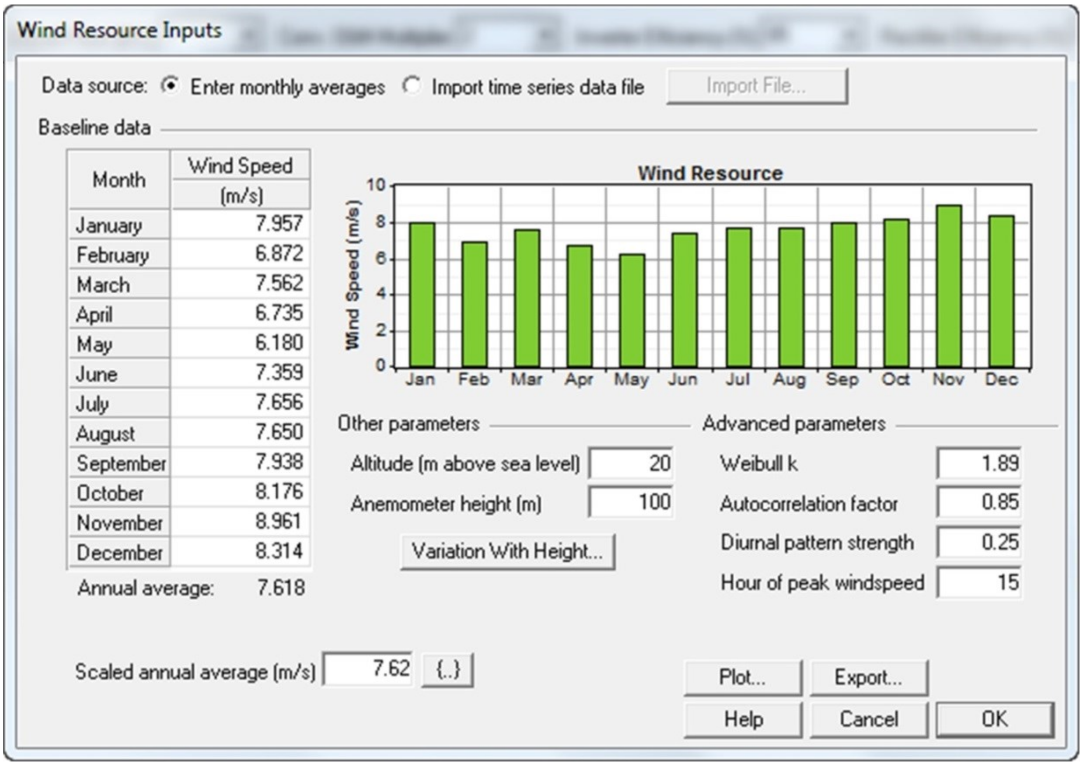
Figure 4. Relationship between costs and PSH components: a) Dams; b) Pumps/turbines installed capacity

C. Wind turbine and resource

The Osorio Wind Park is used as the template for this case study. According to their website (http://www.ventosdosulenergia.com.br), the installed capacity of the project is 150MW, corresponding to 75 identical ENERCON E-70 E4 wind turbines. The power curve for this equipment is offered in the product overview brochure at the ENERCON website (http://www.enercon.de/en-en/88.htm), consulted on September 2014.

The monthly average wind speed in the Osorio Wind Park at 100m above ground was extracted from Silva (2012). According to the author, measures made by the wind park operator found an average annual Weibull shape factor k = 1.89, with the hour of peak wind speed at 15 hours. The Weibull shape factor, with a typical range from 1.5 to 2.5, refers to the shape of a distribution of wind speeds, with higher values indicating that wind speed tend to stay within a narrow range. Figure 5 shows the wind resource inputs used in HOMER.

Based on Braciani (2011), the average cost per installed kilowatt in a wind farm in Brazil is around US$2,156.50/kW. By using this value, the capital cost of each E-70 turbine was set at US$4,313,000 in HOMER.



Wind Resource Inputs

Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

Month	Wind Speed (m/s)
January	7.957
February	6.872
March	7.562
April	6.735
May	6.180
June	7.359
July	7.656
August	7.650
September	7.938
October	8.176
November	8.961
December	8.314

Annual average: 7.618

Other parameters

Altitude (m above sea level) 20

Anemometer height (m) 100

Advanced parameters

Weibull k 1.89

Autocorrelation factor 0.85

Diurnal pattern strength 0.25

Hour of peak windspeed 15

Scaled annual average (m/s) 7.62

Figure 5. Wind resource inputs in HOMER for the case study

D. Generator

For this case study, an AC diesel generator with HOMER's default settings is considered as one of the options to serve the load. Two different diesel prices were evaluated in the sensibility analysis: U$5/L and U$1/L. Several generator sizes were considered, as described in Figure 1, with the technical minimum load ratio set at 30%, according to Kaldellis *et al.* (2010) for heavy oil and diesel engines.

No cost penalties for emissions were assigned in this case study. However, along with the price of fossil fuels, the greenhouse and pollutant gas emissions usually play a significant role in the viability of renewable energy projects. As cited by Glasnovic and Margeta (2011), it is estimated that coal power plants emit 0.955kg CO_2/kWh, oil driven power plants emit 0.893kg CO_2/kWh and gas power plants 0.599kg CO_2/kWh.

For cost calculations in HOMER, the average cost per installed kilowatt for a thermoelectric plant in Brazil is set at US$1,073.50/kW, according to Braciani (2011).

E. Load

The AC load profile used as baseline for this case study was created from data related to Porto Alegre, capital city of Rio Grande do Sul. For non-touristic cities of the state, the behavior of electricity demand trough the seasons is likely to be similar.

Figure 6a presents the scaled monthly load profile, represented as a percentage of the average daily load. This graph was created based on the information reported by Hansen (2000) regarding the total monthly load consumption in Porto Alegre for the years 1997 and 1998. As for the daily profile, Rahde and Kaehler (2000) obtained the typical daily load curve for the residential customer (151 – 300kW·h/month) in Porto Alegre. These hourly values were converted so that they represent the loads in terms of percentage of the total daily load, as shown in Figure 6b.

In order to be used as data source by HOMER, the information from both graphs in Figure 6 was combined to create a load profile with the average electric demand (in kW) for the 8,760 hours in a year. The average baseline demand was set at 100kW·h/d. As previously mentioned, this baseline was scaled to 100MW·h/d and 500MW·h/d, to assess the optimal system configuration for different scenarios by means of the HOMER software features.

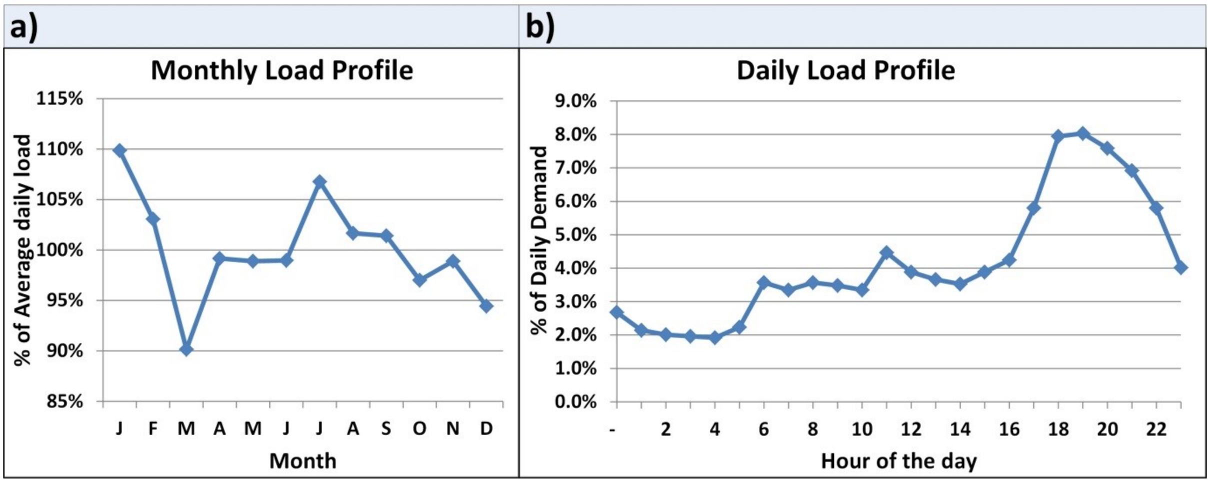


Figure 6. Scaled load profiles for the case study

F. Additional considerations

Besides the information and parameters described before, some other considerations and assumptions were made for modeling the system described in HOMER.

For the operating reserve, the 10% HOMER default value is used, indicating that the system must operate with enough spare capacity to serve an abrupt 10% increase in the load. The maximum acceptable capacity shortage was set at zero and the dispatch policy is the load-following strategy.

The wind power operating reserve was set at 50%, representing that the system must keep enough spare capacity operating to serve the load even if the wind turbine output suddenly decreases 50%. Besides working as spinning reserve, the importance of this reserve is supported by Sovacool (2009), who mentions that, even though is possible to forecast the wind generator output a day in advance, forecast errors of 20%-50% are not unusual.

The project and equipment lifetime was assumed to be 20 years, with HOMER’s default value for the annual real interest rate of 6%. For estimating the operating and maintenance (O&M) cost of the different components, the following values were adopted:

- For a conventional hydropower installation and the hydropower reservoirs (represented as batteries), the O&M annual cost was set as 3% of the capital cost of the equipment, according to Jiandong *et al.* (1997).
- For a pumped storage hydropower installation (not including the reservoir), represented in HOMER by means of the converter, it was assumed an O&M annual cost of 6% of the capital cost, based on the observations made by Sadden (1990), who indicates that the overhauling is twice more frequent than in conventional plants.
- For the wind turbines, it was adopted an O&M annual cost of 4%, a conservative estimate based on Lemming *et al.* (2009). They state that for new large turbines, costs for service, consumables, repair, insurance, administration, lease of site, etc. range from 2 to 3.5% of the capital cost.
- The operating and maintenance cost for the AC diesel generator was assumed to be US$0.01/kW per hour.

IV. SIMULATION AND OPTIMIZATION RESULTS AND DISCUSSION

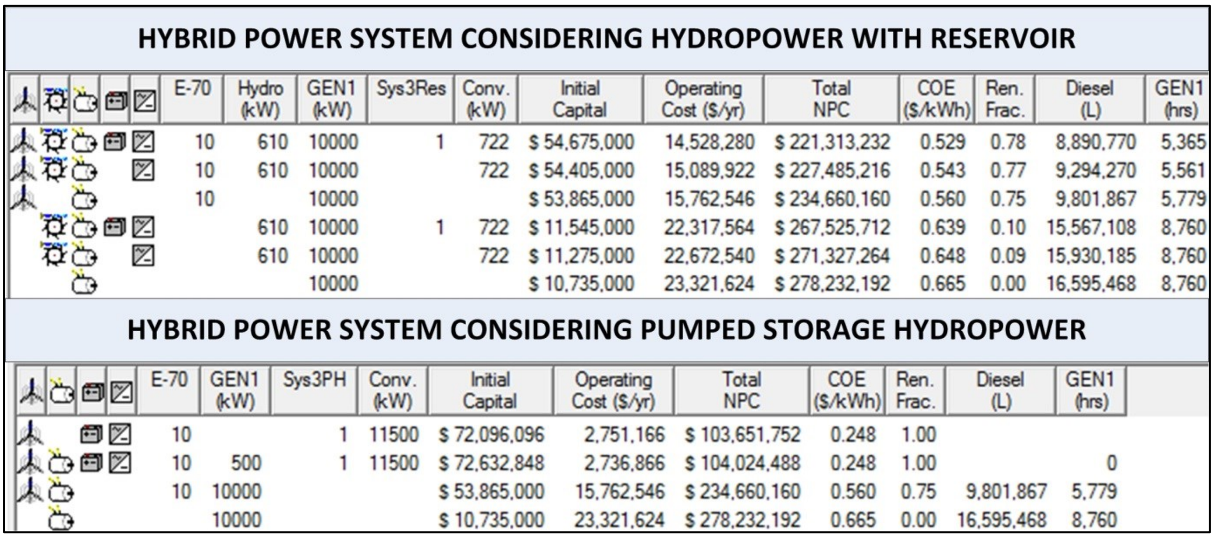
By using the procedures and case study data previously described, the main results obtained by the simulation with HOMER are presented and discussed in this section.

A. Comparing conventional and pumped hydropower at the same site

The procedures explained in the method section allow determining the best use of a site with potential for both conventional and pumped storage hydropower in a hybrid power system. An example of this is shown in Figure 7, where the best options are sorted in terms of the NPC of the feasible system designs. Using the conditions described in the case study presentation, with a scaled annual average primary load of 100MW·h/d and diesel price of US$1/L, some remarks can be made:

- With capacity of less than half of each wind turbine, it was clear since the case study presentation that the conventional hydropower plant with reservoir would probably not be much appealing for a system of this size or bigger. While including this component is the best option in terms of NPC and increases the renewable fraction in 3%, this also does not reduce the size of the required generator or its total run time during the year. This is evident when the system design does not include wind power and the generator must operate 100% of the time.
- A pumped hydropower scheme, while not necessarily adding more renewable electricity to the system, it would enable further integration of variable (or intermittent) sources of renewable energy. For both hydropower options, the best system design for this scenario would include ten E-70 wind turbines. For this load scenario, the difference between them is that the scheme with pumped hydropower (with 11.5MW of installed capacity) does not require a diesel generator, allowing a 100% renewable generation to serve the AC load of 100MW·h/d. The estimated excess energy for the system with pumped hydro is 33.6%, and 56.2% for the scheme with the small hydropower plant.

- The initial capital cost of the system including PSH would be 33% higher when compared to the one with conventional hydropower, mostly because of the additional reservoir and the pump/turbine units of greater capacity. However, after 20 years and with the parameters already defined, the NPC of the system with PSH is only 47% of the other configuration, mainly because the savings on fuel, with less emissions of greenhouse gases as an additional benefit.
- Among the considered sizes for the upper reservoir of the PSH plant, the minimum volume is enough to serve the AC load, as it can be seen in Figure 7 at the column with the number of Sys3PH batteries. According to the tables in Beluco (2012), the flooded area and volume of both PSH reservoirs combined (0.225km²; 4.0hm³) would be less than the one of the conventional hydropower plant (0.561km²; 18.7hm³).



HYBRID POWER SYSTEM CONSIDERING HYDROPOWER WITH RESERVOIR

E-70	Hydro (kW)	GEN1 (kW)	Sys3Res	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	GEN1 (hrs)
10	610	10000	1	722	$ 54,675,000	14,528,280	$ 221,313,232	0.529	0.78	8,890,770	5,365
10	610	10000		722	$ 54,405,000	15,089,922	$ 227,485,216	0.543	0.77	9,294,270	5,561
10		10000			$ 53,865,000	15,762,546	$ 234,660,160	0.560	0.75	9,801,867	5,779
	610	10000	1	722	$ 11,545,000	22,317,564	$ 267,525,712	0.639	0.10	15,567,108	8,760
	610	10000		722	$ 11,275,000	22,672,540	$ 271,327,264	0.648	0.09	15,930,185	8,760
		10000			$ 10,735,000	23,321,624	$ 278,232,192	0.665	0.00	16,595,468	8,760

HYBRID POWER SYSTEM CONSIDERING PUMPED STORAGE HYDROPOWER

E-70	GEN1 (kW)	Sys3PH	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	GEN1 (hrs)
10		1	11500	$ 72,096,096	2,751,166	$ 103,651,752	0.248	1.00		
10	500	1	11500	$ 72,632,848	2,736,866	$ 104,024,488	0.248	1.00		0
10	10000			$ 53,865,000	15,762,546	$ 234,660,160	0.560	0.75	9,801,867	5,779
	10000			$ 10,735,000	23,321,624	$ 278,232,192	0.665	0.00	16,595,468	8,760

Figure 7. HOMER optimization results for both hydropower options. Load: 100MWh/d; Diesel Price: US$1/L

Limited by the geographic and hydrological constraints at this site, the impact of the conventional hydropower plant in the system decreases as the average primary load increases, and thus the number of wind turbines and size of the diesel generator becomes a function of the fuel price and cost of each wind turbine.

Mainly because of the small watershed area above the lower reservoir dam and the corresponding available stream flows, the conventional hydropower potential for this case study is only a fraction of what can be installed for pumped hydropower. The capacity to perform this kind of comparison is particularly important because single dams of hydropower plants can be transformed into pumped hydro if a site suitable for a second reservoir is available. This suitability requires two main conditions: being vertically separated a few hundred meters, but not too distant in the horizontal direction from the existing reservoir. As cited by Fitzgerald *et al.* (2012), this transformation of single reservoirs is perhaps the simplest way to add energy storage capacity to the grid, has lower costs than new pumped hydropower systems and lower environmental impacts than new hydropower plants with reservoir.

B. Pumped hydropower and the capacity for recovering rejected renewable energy

The complete output provided by HOMER for each feasible option allows estimating and optimizing the capacity of PSH for recovering rejected renewable energy. This can also be used for calculating the effective capacity factor of the wind farm with and without the PSH. To achieve this, and also to illustrate the sensitivity of the system design to the diesel price, Table I presents the summarized results for a system with a scaled annual average primary load of 500MW·h/d and two different prices for diesel.

Table I. Output summary for the best system design for 500MWh/d AC Load with different diesel prices

	Description	**Units**	**With Diesel Price = US$1/L**	**With Diesel Price = US$5/L**	**Additional notes**
[1]	ENERCON E-70	Units	40	45	2MW capacity each wind turbine
[2]	Size of the reservoir	m³	1,510,000	3,020,000	1.51x10^6 m³ = 1 battery = 1.93GWh
[3]	Hydropower pumps/turbines	MW	46.1	46.1	85% efficiency for both operating modes
[4]	AC diesel generator	MW	40.0	-	Min. load ratio 30%
[5]	Energy from wind power	GWh	249.6	280.8	Including excess electricity
[6]	Energy consumed by pumps	GWh	91.1	93.2	Rectifier input in HOMER simulation
[7]	Energy produced by hydro turbines	GWh	66.0	67.5	Inverter output in HOMER simulation
[8]	Energy from diesel generator	GWh	5.5	-	
[9]	Excess electricity	GWh	47.5	72.5	
[10]	Total AC Load	GWh	182.5	182.5	
[11]	Net energy from reservoir	GWh	0.2	0.1	
[12]	Final % of volume in the reservoir	%	89.6	96.5	Final state of charge of the battery in HOMER
[13]	Net Present Cost	US$	$379,705,696	$402,920,160	Best system in terms of NPC for each situation

According to the simulation results and based on the wind resource inputs of the case study, the maximum CF of the wind turbines reported by HOMER is 35.6%, including excess electricity. The Osorio Wind Park, used as model for creating the wind turbines of this work, reports on its website a CF = 32.3%. These values are within the range of values reported by Boccard (2009), who gathered global results reported by transmission system operators or available in academic literature related to wind farm capacity factors.

Based on the equation (5) and the output summary presented in Table I, the following observations can be made about these scenarios:

- The influence of the diesel price on the best system configuration is clear. The procedures used in this paper allow benefiting from the sensitivity analysis capabilities of HOMER to assess long-term scenarios. For this case study, the sensitivity graph shown in Figure 8 displays the optimal system type as a function of the diesel price and average primary load. For an average primary load of 500MW·h/d, the results suggest that is better to invest in wind turbines and reservoir capacity when diesel prices are above US$4.91/L.
- If energy storage is not considered, and diesel price at US$1/L, the system configuration required to serve the load would comprise fifty E-70 wind turbines and a 50MW diesel generator. Because of the additional wind turbines and the extended use of the generator, the *NPC* of this system is three times higher than any of the two schemes described in Table I, with 75% of the total electrical production coming from the renewable source. As an additional remark, the excess wind energy of 74.7% and diminutive *CF* (9%) of the wind farm for the case without PSH highlights the importance of energy storage for integrating intermittent renewable sources to the power grids.
- PSH plants are net consumers of energy, but their function is to make better use of other intermittent renewable energies. The scenario with diesel price = US$5/L promotes a system with 100% of the energy production coming from renewable sources. According to these results, it can be easily observed the advantage of energy storage by means of PSH. Even with the energy losses in both directions associated with the processes of pumping water uphill and its later release through the turbines, it is possible to recover 67.5GWh of free and clean energy from the wind farm. This recovered energy, that otherwise would have been rejected, represents 24% of the total available wind energy. The resulting wind farm CF of 23.1% would have been only 14.6% without energy storage.

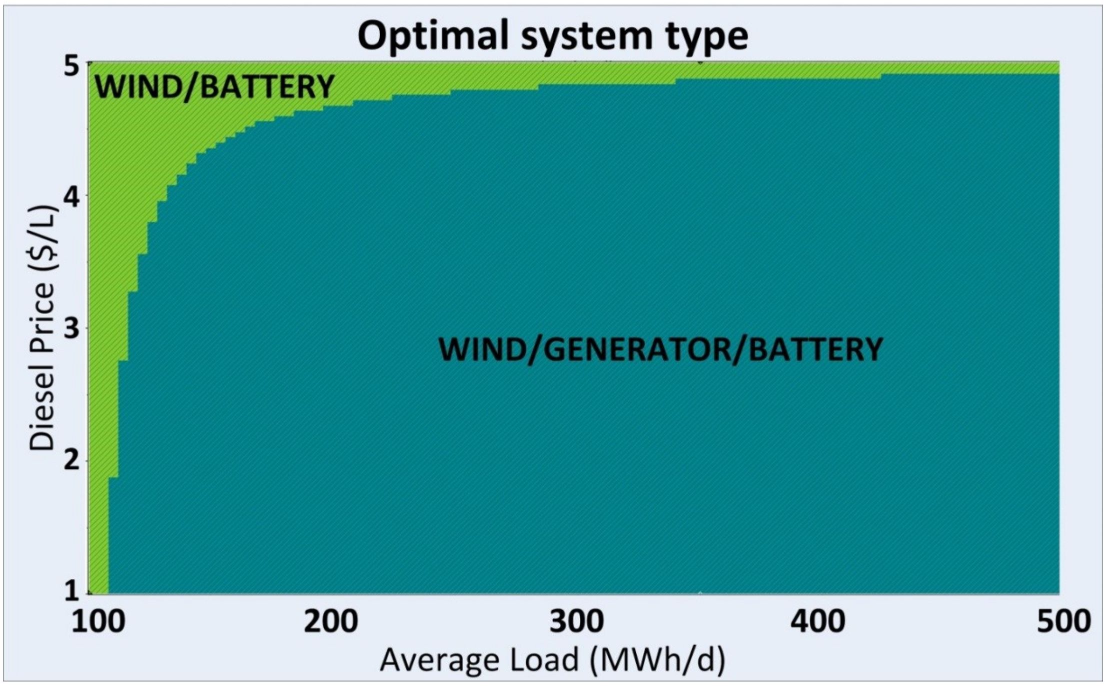


Figure 8. Sensitivity graph of the optimal system type based on diesel price and average primary load

Based on the results obtained in simulations, Figure 9 presents the estimated duration curves for rejected power. As explained by Kaldellis *et al.* (2010), large amounts of rejected energy also mean severe financial losses that discourage future investments in renewable energy projects. Without the PSH, the extremely variable wind profile would require more turbines at the wind farm along with a diesel generator of greater capacity, thus increasing the generation cost. As shown in Figure 9a, a system without storage capacity would reject power about 80% of the time, with 25% of the time rejecting more than 50MW. Conversely, with PSH and using the same 50% of the wind farm capacity as benchmark, Figure 9b and Figure 9c show that this energy storage technology improves the wind energy absorption, limiting the occurrence of this value to less than 10% of the time and reducing the cost of energy (COE) for the system. In HOMER, the COE is the average cost per kWh of useful electrical energy produced by the system, which in this case is just the energy used to serve the primary AC Load (no grid sales, DC or deferrable loads are considered in the example).

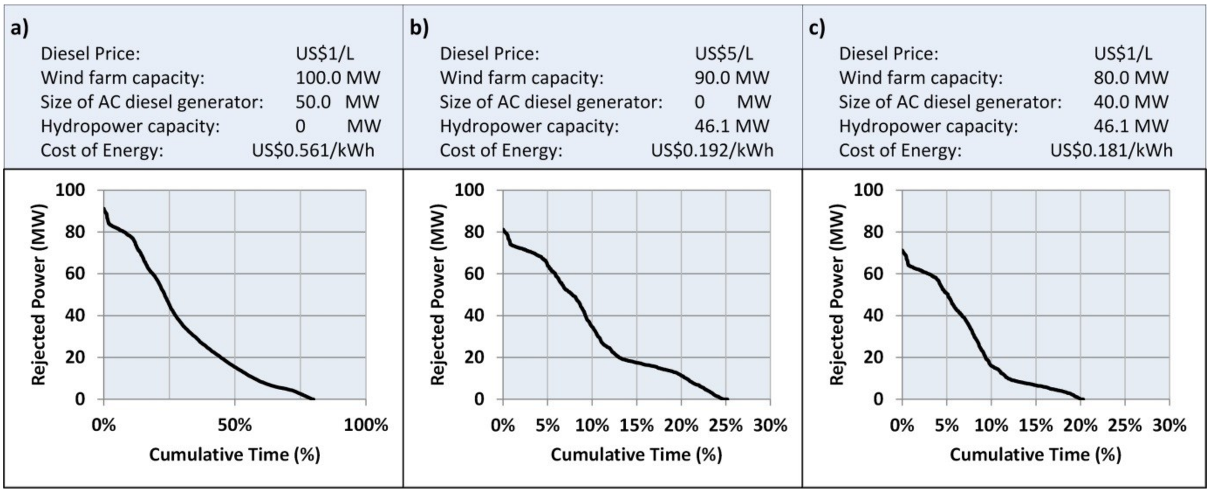


Figure 9. Rejected power duration curves for an average daily load = 500MWh/d

C. Additional remarks

The range of COE values obtained for the different system configurations of this case study is higher than the range published by the Electric Energy National Agency (*Agência Nacional de Energia Elétrica* – ANEEL) of Brazil. According to ANEEL (2008), and using the same currency exchange rate applied before, the COE in Brazil ranges from US$0.05/kWh (small hydro and biomass) to US$0.25/kWh (diesel). Besides the considerations made about the cost of the components, the main reasons for this difference are: 1) The simplification of assuming 20 years as the project lifetime and of all its components; 2) The wind profile characteristics, with a maximum attainable capacity factor of 35.6% for the wind turbines. A more uniform wind profile and a more accurate lifetime of each component would reduce the COE values found by HOMER (e.g., the adopted lifetime of civil works in hydropower projects is usually between 30 and 40 years).

Another factor affecting the COE value is the amount of excess electricity, which could be sold to another grid or used to supply power to deferrable loads, instead of rejecting it by leaving wind turbines offline. Papavasiliou and Oren (2008) indicate that there are several large-scale industrial and commercial deferrable loads that might use this excess electricity, such as thermal storage, heating, air conditioning, pumps, agitators, smelters, wastewater and desalination plants, among others. The plug-in electric vehicles are also an emerging source of flexibility which could revolutionize the ability to incorporate intermittent renewable energy sources, with some test projects in Denmark and California in the process of implementation.

V. CONCLUSIONS

Increasing the share of renewable energies in the total energy supply is a priority for many countries, caused by economic, environmental and climate change concerns. Unlike fossil fuel power plants, renewable energy sources have a significant impact on the reduction of greenhouse and pollutant gas emissions. However, there are concerns over the ability to effectively integrate large amounts of intermittent power generation, such as solar or wind power, into the electrical grid (CHANG *et al*. 2013). Therefore, the main issue for the successful integration of these technologies is how to best manage the intermittency and stochastic nature associated to most of them. Hydropower reservoirs (of conventional and PSH plants) are the most mature and widely used technology to provide dispatchable power and large-scale energy storage, two of the main solutions implemented for a better integration of renewable energies.

This paper presented a method to perform a preliminary assessment of the optimal configuration of an autonomous hybrid power system that includes intermittent renewable energy sources and hydropower reservoirs. The whole set of feasible configurations is also found. The method exploits the available features of the Legacy Version of HOMER, the most widely used tool in research studies related to hybrid power systems. The procedures described in this paper are based on the work by Canales and Beluco (2014), where they modelled a hydropower reservoir as an equivalent battery in HOMER. A case study created from data related to Rio Grande do Sul, Brazil, is described and modeled to validate the method explained in this document.

Among the main findings of this study, the results show that the procedures explained are useful to define the best use of a site with potential for both conventional hydropower and PSH in a hybrid power system, and that the selection and optimal sizing of one of these options depends on many factors such as hydrological constraints, average load to serve and costs of other energy sources. Additionally, under some conditions and combined with intermittent renewable sources, it was observed that PSH is an efficient way to minimize costs with additional environmental benefits when compared to fossil fuel power plants (PSH produces less emissions) or conventional hydropower with reservoir (PSH can have more installed capacity with less area and reservoir volume).

The procedures explained in this paper allowed quantifying the capacity for recovering excess renewable energy by means of PSH, and the positive impact of the electricity storage on the capacity factor of a renewable plant. The results showed that the storage option considerably decreases the amount of rejected energy, the use of thermal units, initial cost of the system and COE values.

For each sensitivity case, the simulation and optimization processes of HOMER sort the feasible system configurations in terms of their Net Present Cost. However, the detailed output of the overall optimization results can be saved as a plain text file, and this can be used to identify other optimal solutions (*e.g.*: in terms of renewable fraction, excess electricity or Pareto optima) by means of data processing.

The method described in this paper benefits from some important characteristics of HOMER. The model is the most widely used and proven software tool for hybrid power systems, has optimization and sensitivity analysis capabilities, and it also provides a detailed output for a simulation period of 8760 hours for each feasible configuration. Correspondingly, besides the lack of a specific component for reservoirs, which can be overcome by using an equivalent battery, the procedures of this work are affected by some limitations of the current releases of HOMER (*e.g.*: optimization is single-objective, only the operation of fuel generators can be scheduled). Future or custom versions of HOMER could address these limitations, but the Legacy version was selected due to its universal access. The procedures and results presented in this document could be useful as guidelines for developing similar models.

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6. CONCLUSÕES E RECOMENDAÇÕES

Este trabalho apresentou um conjunto de métodos utilizados com o propósito de resolver o seguinte problema de pesquisa: *Como determinar, de forma preliminar, a melhor configuração de um sistema híbrido autônomo de geração de energia elétrica que inclua fontes renováveis intermitentes e reservatórios hidrelétricos?*

A principal ferramenta de análise utilizada ao longo do presente trabalho é a versão *Legacy* v2.68 do *software* HOMER (*Hybrid Optimization Model for Electric Renewables*), o modelo mais amplamente utilizado em pesquisas relacionadas a sistemas híbridos de energia (SINHA & CHANDEL, 2014). Os principais motivos para selecionar o HOMER foram: (i) é uma ferramenta amplamente testada e confiável em estudos relacionados a sistemas híbridos de geração; (ii) a versão Legacy está disponível gratuitamente; (iii) permite a criação de baterias com características especificadas pelo usuário; (iv) possui um módulo de otimização (v) permite realizar diretamente análises de sensibilidade.

Com exceção de um exemplo 100% hipotético, os estudos de caso utilizados para validar os métodos propostos foram criados a partir de dados reais do Estado de Rio Grande do Sul. Neste contexto e com base nos dados utilizados e resultados obtidos, as principais conclusões e recomendações se apresentam neste capítulo.

6.1 Conclusões

As preocupações ambientais, o encarecimento dos combustíveis fósseis, o aperfeiçoamento das tecnologias e a disponibilidade de recursos têm sido fatores responsáveis pelo crescente interesse mundial nas energias renováveis para geração de eletricidade em todo o mundo. Segundo a *International Renewable Energy Agency* (IRENA, 2014), a participação das energias renováveis na matriz energética mundial poderia passar da percentagem atual de 18% para 36% em 2030.

A imprevisibilidade das principais fontes de energia renovável (e.g.: solar e eólica), em diferentes escalas de tempo, acarreta desafios na operação dos sistemas de geração e distribuição de energia elétrica, principalmente no relacionado à regulação de frequência na rede, mantida através do equilíbrio entre geração e carga. A melhor solução para este problema, segundo Faias et al. (2009) e Castronuovo e Usaola (2013), é o armazenamento de energia, que permite controlar a produção de eletricidade e recuperar parte do excedente produzido por fontes renováveis intermitentes.

Para aproveitamento em grande escala, os reservatórios hidrelétricos (de usinas hidrelétricas convencionais com reservatório e usinas reversíveis) são a tecnologia mais madura e amplamente utilizada para armazenamento de energia elétrica na forma de energia potencial no volume de água. Por esta razão esta tecnologia é um componente importante a ser considerado em projetos de sistemas autônomos híbridos de geração de energia.

A configuração e dimensionamento adequado de sistemas híbridos de geração são essenciais para a utilização eficiente dos recursos energéticos renováveis, reduzindo os custos de instalação e minimizando os custos de produção de eletricidade. O programa de *software* mais utilizado no mundo para este propósito é o HOMER, que permite realizar rapidamente estudos de pré-viabilidade, determina a configuração ótima do sistema em função do custo presente líquido do arranjo e permite realizar análises de sensibilidade para múltiplas condições possíveis. Entretanto, versões atuais do HOMER (e de outros modelos similares) não incluem um componente específico para modelar reservatórios hidrelétricos, o que limita sua aplicabilidade.

Neste trabalho foi comprovado que pode estabelecer-se uma analogia entre os reservatórios hidrelétricos e as baterias elétricas, com relação aos seus processos de armazenamento e entrega de energia. Com base nisso, foi possível representar reservatórios hidrelétricos como baterias equivalentes aproveitando a função do HOMER que permite criar baterias personalizadas, conforme os métodos detalhados nos capítulos 3 e 4. Os procedimentos e considerações adotadas foram validados através dos estudos de caso. Os resultados indicam que a representação como baterias equivalentes permite modelar eficazmente alguns dos principais processos dos reservatórios hidrelétricos de usinas convencionais e reversíveis, por exemplo: esvaziamento e recarga dos reservatórios, armazenamento de energia, potência instalada das bombas/turbinas e a potência gerada em função da vazão turbinada.

A validação dos procedimentos explicados nos capítulos 3 e 4 permitiu examinar algumas das aplicações e potencial destes métodos na simulação e otimização de sistemas autônomos híbridos de geração de energia, segundo o apresentado no capítulo 5.

A capacidade de representar ambos os tipos de reservatórios hidrelétricos no HOMER possibilitou a comparação do desempenho de usinas hidrelétricas com reservatório e UHER em um sítio onde ambas as tecnologias poderiam ser aproveitadas. Sob algumas condições, e em conjunto com fontes renováveis intermitentes, observou-se que as usinas reversíveis são uma alternativa eficiente para minimizar o custo presente líquido dos sistemas híbridos de geração. Adicionalmente, são capazes de render benefícios ambientais adicionais quando comparadas com usinas termelétricas (UHER gera menores emissões de gases de efeito estufa) ou usinas hidrelétricas convencionais com reservatório (as UHER podem ter uma capacidade instalada maior com áreas alagadas e volumes menores).

Devido às perdas de eficiência em ambos os processos, poderia parecer ilógica a ideia de bombear água a uma altura de várias dezenas de metros só para deixá-la cair de novo e movimentar turbinas hidráulicas. Entretanto, a maturidade da tecnologia, a quantidade de projetos e capacidade instalada em países desenvolvidos, confirma que as usinas hidrelétricas reversíveis são, até hoje, a melhor opção para armazenamento de energia elétrica em grande escala. Adicionalmente, novos arranjos de UHER vêm sendo desenvolvidos, visando diminuir os impactos ambientais e maximizar a capacidade de armazenamento e potência.

Por consumirem mais energia da que conseguem gerar, as UHER não podem ser consideradas como centrais geradoras. Contudo, sua função é amortecer os impactos da variabilidade que apresentam outras fontes renováveis de energia, através da acumulação e recuperação de parte da eletricidade excedente produzida principalmente em parques eólicos e solares. Os métodos descritos no capítulo 5 do presente trabalho possibilitam quantificar o excedente de energia intermitente que poderia ser recuperado, e o impacto positivo do armazenamento no fator de capacidade de uma central renovável. No exemplo utilizado, e considerando uma UHER como dispositivo de armazenamento de um parque eólico, foi observado que esta tecnologia permite diminuir consideravelmente o desperdiço de energia renovável, o uso de termelétricas e os custos iniciais e de geração do sistema.

Os resultados obtidos para o sistema híbrido do estudo de caso evidenciaram que a configuração do sistema e o tamanho ótimo dos componentes dependem de muitos fatores como: restrições topográficas e hidrológicas, carga a ser atendida e custos de geração das diferentes fontes. Neste trabalho, diferentes condições de custos e carga foram avaliadas mediante o *software* HOMER. Através desta ferramenta foi possível determinar a configuração ótima (em termos do custo presente líquido) e o conjunto de arranjos viáveis de um sistema autônomo de geração de energia incluindo fontes renováveis intermitentes e reservatórios hidrelétricos.

Com base nos parágrafos anteriores, observa-se que os objetivos propostos no início deste trabalho foram alcançados. Igualmente, os resultados obtidos por meio dos métodos explicados na presente tese permitem afirmar que, em nível de pré-viabilidade, **é possível determinar a configuração mais eficiente de um sistema híbrido autônomo de geração de energia elétrica que inclua fontes renováveis intermitentes e reservatórios hidrelétricos.**

6.2 Recomendações

Os objetivos propostos deste trabalho foram atingidos; porém, é preciso agregar algumas considerações, limitações e cuidados que surgiram durante o processo de elaboração do mesmo, os quais são incluídos nestas recomendações:

- Os procedimentos explicados neste trabalho aproveitam as funcionalidades da versão *Legacy* v2.68 do *software* HOMER para representar reservatórios hidrelétricos na forma de baterias equivalentes. Uma limitação disto é que a altura de queda deve ser considerada constante, portanto, esta altura deve ser definida de forma que represente o comportamento médio do sistema. Outra opção seria utilizar a altura mínima disponível, como medida de segurança.
- O HOMER simula o funcionamento do sistema durante um período de 8760 horas (um ano), de modo que a depleção máxima do reservatório no final deste período deve ser levada em consideração no início do ano seguinte.
- O processo de otimização no HOMER é realizado de forma que simula todas as configurações possíveis do sistema, na procura por aquela que satisfaça todas as restrições técnicas com o menor custo presente líquido. Contudo, o resumo dos resultados de todos os arranjos viáveis pode ser salvo como um arquivo de texto simples, que pode ser processado a fim de encontrar outras soluções ótimas locais (em termos de parcela de energia de fontes renováveis, excedente de energia gerada, etc.). O processamento destes dados também permitiria encontrar soluções multiobjetivo (*i.e.*: Ótimos de Pareto).
- Futuras versões do HOMER (ou de outros softwares similares) poderiam incluir elementos para a modelagem específica de reservatórios hidrelétricos. A versão *Legacy* v2.68 do *software* HOMER foi escolhida por estar disponível gratuitamente e por ser amplamente utilizada em pesquisas relacionadas a sistemas híbridos de geração de energia, no nível de estudos de pré-viabilidade.
- No HOMER, o custo de geração de energia (COE) é calculado como o custo médio por kWh de energia utilizada (sem incluir excesso de geração). Segundo a Agência Nacional de Energia Elétrica (ANEEL, 2008) a faixa de valores para o COE no Brasil varia de US$0.05/kWh (Pequenas centrais hidrelétricas e biomassa) até US$0.25/kWh (diesel). Em alguns cenários dos estudos de caso, o COE obtido foi superior a estes valores. Além das considerações relacionadas aos custos dos componentes, as principais causas desta diferença foram: (i) a simplificação de assumir 20 anos de vida útil para os projetos e todos seus elementos; (ii) a grande variabilidade existente nos regimes de vento utilizados nos estudos de caso. Ventos mais uniformes e ciclos de vida mais precisos produziriam valores de COE menores. Por exemplo, Jiandong *et al.* (1997) afirmam que a vida útil de obras civis (como barragens) em projetos hidrelétricos estima-se entre 30 e 40 anos.

Os métodos aqui apresentados podem ser utilizados como diretrizes na criação e validação de ferramentas semelhantes. Para a realização de pesquisas futuras que abordem os temas tratados na presente tese sugere-se:

- A criação de modelos similares para análise de sistemas híbridos que permitam representar reservatórios hidrelétricos (de centrais convencionais e UHER) de forma mais eficiente, incluindo a potência em função da altura de queda variável e a simulação da operação do sistema para períodos maiores que um ano. A variabilidade das fontes renováveis em períodos menores que uma hora e a otimização multiobjetivo também poderiam ser levadas em consideração.
- Avaliar o impacto e integração de usinas hidrelétricas reversíveis no Sistema Interligado Nacional. Por causa das demandas de processamento requeridas na representação de um sistema deste porte, poderia ser útil a figura dos reservatórios equivalentes, segundo o explicado por Arvanitidis e Rosing (1970).

6.3 Referências

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ANEXO A – Seleção de conteúdos extraídos da documentação do *software* HOMER

Constraints

Constraints are conditions which **systems** must satisfy. HOMER discards systems that do not satisfy the specified constraints, so they do not appear in the optimization results or sensitivity results.

Variable	Description
Maximum annual capacity shortage	The maximum allowable value of the **capacity shortage fraction**, which is the **total capacity shortage** divided by the total annual electric load.
Minimum renewable fraction	The minimum allowable value of the annual **renewable fraction**.

Operating reserve

> **Note:** Under most circumstances you do not need to change the values of these advanced inputs. Their default values are appropriate for most systems.

Operating reserve is surplus **operating capacity** that ensures reliable electricity supply even if the load suddenly increases or renewable power output suddenly decreases. HOMER defines the required amount of operating reserve using four inputs, two related to the variability of the electric load and two related to the variability of the renewable power. These four inputs are described in the article on **required operating reserve**. The total required operating reserve is the sum of the four values resulting from these four inputs. In its simulation, HOMER operates the power system so as to keep the operating reserve equal to or greater than the required operating reserve. Any shortfall is recorded as a **capacity shortage**.

Variable	Description
As a percent of hourly load	HOMER adds this percentage of the hourly average primary load (AC and DC separately) to the **required operating reserve** for each hour. A value of 10% means that the system must keep enough spare capacity operating to serve a sudden 10% increase in the load.
As a percent of annual peak load	HOMER adds this percentage of the peak primary load (AC and DC separately) to the **required operating reserve** for each hour. It therefore defines a constant amount of operating reserve. For example, if the peak AC primary load is 40 kW and you want to ensure at least 8 kW of operating reserve on the AC bus at all times (maybe to cover an 8 kW motor starting load), set this input to 20%.
As a percent of wind power output	HOMER adds this percentage of the wind turbine power output to the **required operating reserve** for each hour. A value of 60% means that the system must keep enough spare capacity operating to serve the load even if the wind turbine output suddenly decreases 60%. The more variable you expect the output of the wind turbine to be, the higher you should set this input.
As a percent of solar power output	HOMER adds this percentage of the PV array power output to the **required operating reserve** for each hour. A value of 25% means that the system must keep enough spare capacity operating to serve the load even if the PV array output suddenly decreases 25%. In most cases, the output of the PV array

	should be less variable than the output of a wind turbine, so this input will usually be set at a lower value than the previous one.

To the right of each input is a sensitivity button which allows you to do a **sensitivity analysis** on that variable.

See also

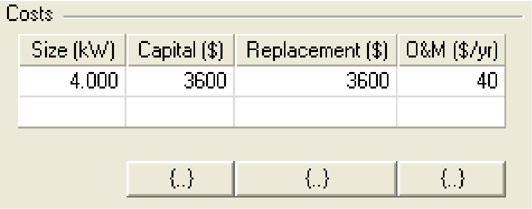
Operating reserve
Required operating reserve

Written by: Tom Lambert (**tom@homerenergy.com**)
Last modified: May 26, 2004

Converter Inputs

Any system that contains both AC and DC elements requires a converter. This window allows you to define the cost curve of the converter and choose the sizes you want HOMER to consider as it searches for the optimal system.

Costs

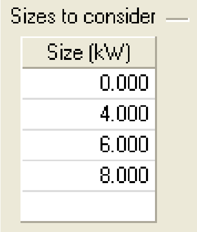


Size (kW)	Capital ($)	Replacement ($)	O&M ($/yr)
4.000	3600	3600	40

In the cost table, enter the converter's *cost curve*, meaning the way its cost varies with size. In the sample shown above, the capital and replacement cost of a 4 kW converter is specified at $3,600/kW. When specifying the capital and replacement costs, remember to account for all costs associated with the converter, including installation.

Note that the **capital cost** is the initial purchase price, the **replacement cost** is the cost of replacing the converter at the end of its lifetime (relevant only if the **project lifetime** exceeds the converter lifetime), and the operating and maintenance cost is the annual cost of operating and maintaining the converter.

Sizes to consider



Size (kW)
0.000
4.000
6.000
8.000

In this table, enter the converter sizes you want HOMER to consider as it searches for the optimal system. Be sure to include a zero size if you want to consider systems without converters. HOMER will use the information you entered in the cost table to calculate the costs of each converter size, interpolating and extrapolating as necessary. You can see the results in the cost curve graph.

> **Note:** You can also access the values in this table using the **Search Space** window.

Inverter inputs

An inverter converts DC electricity to AC electricity.

Variable	Description

Lifetime	The expected lifetime of the inverter, in years.
Efficiency	The efficiency with which the inverter converts DC electricity to AC electricity, in %.
Inverter can operate simultaneously with an AC generator	Check this box if the inverter can operate at the same time as one or more AC generators. Inverters that are not able to operate this way are sometimes called switched inverters.

Rectifier inputs

A rectifier converts AC electricity to DC electricity.

Variable	Description
Capacity relative to inverter	The rated capacity of the rectifier relative to that of the inverter, in %.
Efficiency	The efficiency with which the rectifier converts AC electricity to DC electricity, in %.

To the right of each numeric input is a sensitivity button which allows you to do a **sensitivity analysis** on that variable.

Note that HOMER assumes the inverter and rectifier efficiencies are constant. In fact, most solid-state converters are less efficient at very low load because of standing losses. **Hybrid2** accounts for these standing losses.

Written by: Tom Lambert (**tom@homerenergy.com**)
Last modified: October 29, 2004

How HOMER Calculates the Hydro Power Output

In each time step, HOMER calculates the electrical power output of the hydro turbine using the following equation:

$$P_{hyd} = \frac{\eta_{hyd} \cdot \rho_{water} \cdot g \cdot h_{net} \cdot \dot{Q}_{turbine}}{1000\ W/kW}$$

where:

P_{hyd} = power output of the hydro turbine [kW]

η_{hyd} = **hydro turbine efficiency** [%]

ρ_{water} = density of water [1000 kg/m^3]

g = acceleration due to gravity [9.81 m/s^2]

h_{net} = **effective head** [m]

$\dot{Q}_{turbine}$ = **hydro turbine flow rate** [m^3/s]

See also

Nominal hydro power

Written by: Tom Lambert (**tom@homerenergy.com**)
Last modified: December 27, 2007

Levelized Cost of Energy

Type: Output Variable
Units: $/kWh
Symbol: COE

HOMER defines the levelized cost of energy (COE) as the average cost per kWh of useful electrical energy produced by the system. To calculate the COE, HOMER divides the annualized cost of producing electricity (the total annualized cost minus the cost of serving the thermal load) by the total useful electric energy production. The equation for the COE is as follows:

$$COE = \frac{C_{ann,tot} - c_{boiler} E_{thermal}}{E_{prim,AC} + E_{prim,DC} + E_{def} + E_{grid,sales}}$$

where:

$C_{ann,tot}$ = **total annualized cost** of the system [$/yr]
c_{boiler} = **boiler marginal cost** [$/kWh]
$E_{thermal}$ = total thermal load served [kWh/yr]
$E_{prim,AC}$ = **AC primary load served** [kWh/yr]
$E_{prim,DC}$ = **DC primary load served** [kWh/yr]
E_{def} = **deferrable load served** [kWh/yr]
$E_{grid,sales}$ = total grid sales [kWh/yr]

The second term in the numerator is the portion of the annualized cost that results from serving the thermal load. In systems that do not serve a thermal load ($E_{thermal}$=0) this term will equal zero.

The COE is a convenient metric with which to compare systems, but HOMER does not rank systems based on COE. For an explanation, please refer to **Why does HOMER rank systems by total NPC**?

Written by: Tom Lambert (**tom@homerenergy.com**)
Last modified: May 16, 2005

Operating Capacity

The operating capacity is the total amount of electrical generation capacity that is operating (and ready to produce electricity) at any one time. It is therefore the maximum amount of electrical load that the system could serve at a moment's notice.

To ensure reliable supply, the operating capacity should be greater than the electric load. The difference between the operating capacity and the electric load is the **operating reserve**. As it simulates the power system, HOMER attempts to keep the operating reserve equal to or greater than the **required operating reserve**.

In HOMER, both dispatchable power sources (generators, grid, battery bank) and renewable power sources (wind, solar, hydro) provide operating capacity. The operating capacity of a dispatchable source is equal to the maximum amount of power it could produce at a moment's notice. For example:

- A generator that is not currently operating provides no operating capacity because it cannot be counted on to provide power at a moment's notice. It must first be started, allowed to warm up, and synchronized.
- A 50 kW generator that is operating provides 50 kW of operating capacity, regardless of the actual amount of power it is producing at any time.
- The operating capacity provided by the grid is equal to the **maximum grid demand**.
- The operating capacity provided by the battery bank is equal to the maximum amount of power it could discharge at a particular time. It therefore depends on the battery bank's state of charge and its recent charge and discharge history. For more information please see the article on the **kinetic battery model**.

The operating capacity provided by a non-dispatchable renewable source (like a PV array or a wind turbine) is equal to the amount of power the source is currently producing, not the maximum amount of power it could produce. Since a renewable power source cannot be controled like a dispatchable source can, its maximum capacity is not relevant in this context. So a wind turbine with a rated capacity of 50 kW that is only producing 13 kW provides only 13 kW of operating capacity.

HOMER keeps track operating capacity and operating reserve separately for the AC and DC buses. For more information please see **operating reserve**.

Written by: Tom Lambert (**tom@homerenergy.com**)
Last modified: May 6, 2004

Optimization Results

For each **sensitivity case** that it solves, HOMER simulates every system in the **search space** and ranks all the **feasible** systems according to increasing **net present cost**. The **Optimization Results** tab of HOMER's main window displays that list of systems.

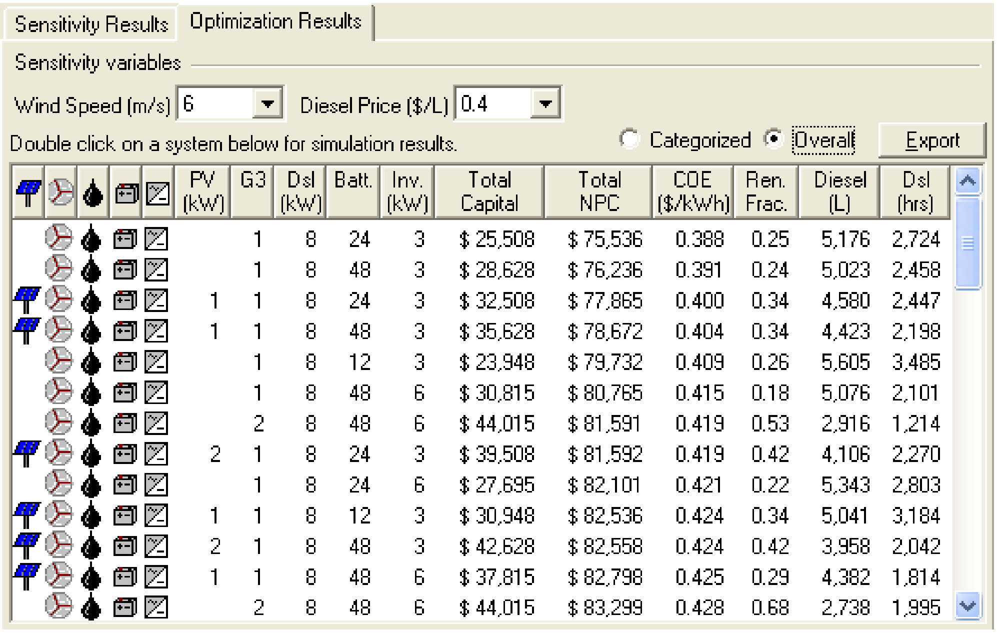
You can get to the **Optimization Results** tab by clicking directly on it, or by clicking on a row in the tabular **sensitivity outputs**. Sensitivity variables appear in drop-down boxes at the top of the tab. Choose the sensitivity case by selecting a value from each drop-down box. HOMER updates the list of systems each time you make a selection from one of the drop-down boxes.

The radio buttons at the top of the list of optimization results let you filter the list of feasible systems according to system type. The two choices, **Overall** and **Categorized**, are explained below.

Overall

If you choose to display the overall system rankings, HOMER shows the top-ranked **system configurations** according to net present cost. (You can set the maximum size of this list in the **Preferences** window.) An example is shown below. If you look closely, you'll see that the icons indicate the presence of each type of component under consideration. In this example the icons indicate the presence of, from left to right: PV panels, wind turbines, the diesel generator, batteries, and the converter. To the right are several columns that indicate the sizes and quantities of the components, plus a few summary values drawn from the simulation results of the least-cost system, such as the total capital cost, total net present cost, and levelized cost of energy.

> **Tip:** Double click any system in the list to see detailed **Simulation Results**.



Wind Speed (m/s) 6
Diesel Price ($/L) 0.4

Double click on a system below for simulation results.

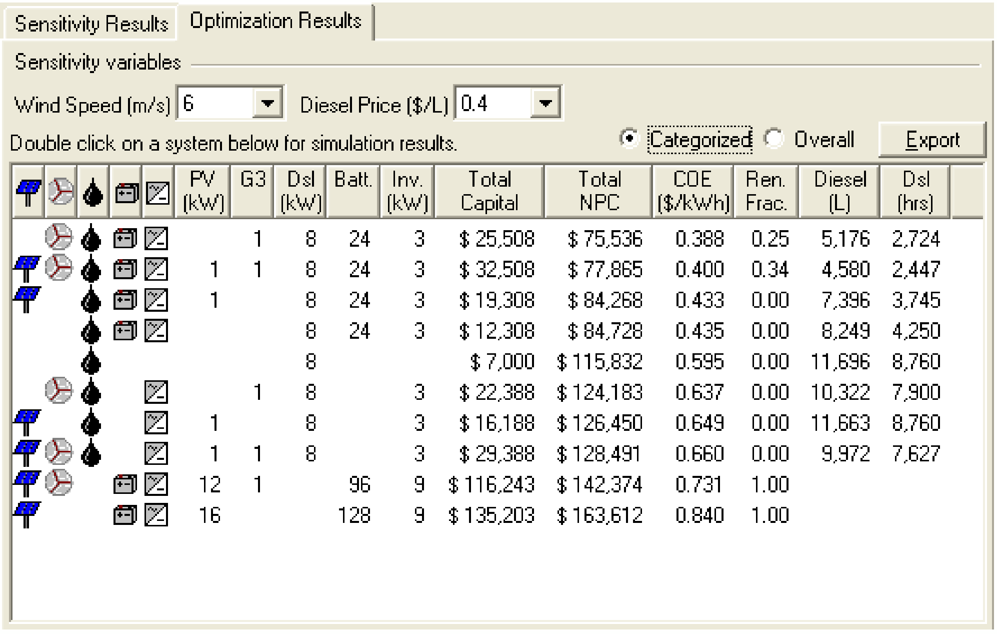
○ Categorized ● Overall

					PV (kW)	G3	Dsl (kW)	Batt.	Inv. (kW)	Total Capital	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Dsl (hrs)
	✓	✓	✓	✓		1	8	24	3	$ 25,508	$ 75,536	0.388	0.25	5,176	2,724
	✓	✓	✓	✓		1	8	48	3	$ 28,628	$ 76,236	0.391	0.24	5,023	2,458
✓	✓	✓	✓	✓	1	1	8	24	3	$ 32,508	$ 77,865	0.400	0.34	4,580	2,447
✓	✓	✓	✓	✓	1	1	8	48	3	$ 35,628	$ 78,672	0.404	0.34	4,423	2,198
	✓	✓	✓	✓		1	8	12	3	$ 23,948	$ 79,732	0.409	0.26	5,605	3,485
	✓	✓	✓	✓		1	8	48	6	$ 30,815	$ 80,765	0.415	0.18	5,076	2,101
	✓	✓	✓	✓		2	8	48	6	$ 44,015	$ 81,591	0.419	0.53	2,916	1,214
✓	✓	✓	✓	✓	2	1	8	24	3	$ 39,508	$ 81,592	0.419	0.42	4,106	2,270
	✓	✓	✓	✓		1	8	24	6	$ 27,695	$ 82,101	0.421	0.22	5,343	2,803
✓	✓	✓	✓	✓	1	1	8	12	3	$ 30,948	$ 82,536	0.424	0.34	5,041	3,184
✓	✓	✓	✓	✓	2	1	8	48	3	$ 42,628	$ 82,558	0.424	0.42	3,958	2,042
✓	✓	✓	✓	✓	1	1	8	48	6	$ 37,815	$ 82,798	0.425	0.29	4,382	1,814
	✓	✓	✓	✓		2	8	48	6	$ 44,015	$ 83,299	0.428	0.68	2,738	1,995

Categorized

The overall rankings are typically dominated by two or three **system types**. In the above example, the top systems are all either wind/generator/battery or PV/wind/generator/battery systems. For a broader comparison, click the ratio button labeled **Categorized**. The categorized rankings show the least-cost system of each type. In the example shown below, the top-ranked system corresponds to the top-ranked system in the overall rankings shown above. But the second system listed corresponds to the third-place system in the overall rankings, because the second-place system in the overall rankings was of the same type as the first-place system. The fifth and ninth systems in the categorized rankings are interesting for comparison because they represent the least-cost pure diesel and completely renewable-powered systems, respectively. They would both appear so far down the overall rankings that they would be hard to see. But the categorized rankings makes it easy to compare these systems with the other alternatives.

Tip: Double click any system in the list to see detailed **Simulation Results**.



Wind Speed (m/s) 6 Diesel Price ($/L) 0.4

Double click on a system below for simulation results. ● Categorized ○ Overall

					PV (kW)	G3	Dsl (kW)	Batt.	Inv. (kW)	Total Capital	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Dsl (hrs)
	✓	✓	✓	✓		1	8	24	3	$ 25,508	$ 75,536	0.388	0.25	5,176	2,724
✓	✓	✓	✓	✓	1	1	8	24	3	$ 32,508	$ 77,865	0.400	0.34	4,580	2,447
✓		✓	✓	✓	1		8	24	3	$ 19,308	$ 84,268	0.433	0.00	7,396	3,745
		✓	✓	✓			8	24	3	$ 12,308	$ 84,728	0.435	0.00	8,249	4,250
		✓					8			$ 7,000	$ 115,832	0.595	0.00	11,696	8,760
	✓	✓		✓		1	8		3	$ 22,388	$ 124,183	0.637	0.00	10,322	7,900
✓		✓		✓	1		8		3	$ 16,188	$ 126,450	0.649	0.00	11,663	8,760
✓	✓	✓		✓	1	1	8		3	$ 29,388	$ 128,491	0.660	0.00	9,972	7,627
✓	✓		✓	✓	12	1		96	9	$ 116,243	$ 142,374	0.731	1.00		
✓			✓	✓	16			128	9	$ 135,203	$ 163,612	0.840	1.00		

See also

Sensitivity results

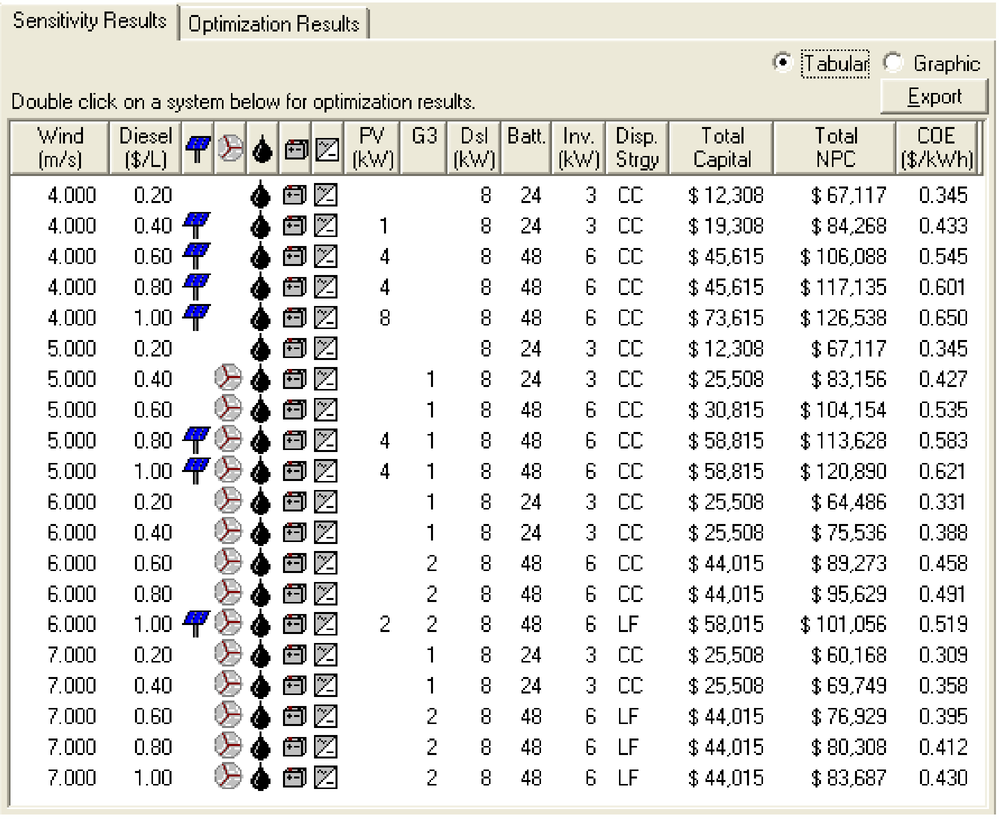
Written by: Tom Lambert (**tom@homerenergy.com**)
Last modified: May 6, 2004

Sensitivity Results

A **sensitivity analysis** can result in a huge amount of output data. Every simulation that HOMER performs results in several dozen summary outputs (like the annual fuel consumption and the total capital cost) plus about a dozen arrays of hourly data (like the hourly output of the wind turbine). HOMER typically performs hundreds or thousands of these simulations per **sensitivity case**, and a sensitivity analysis can easily involve hundreds of sensitivity cases. We designed HOMER's graphic and tabular output capabilities to let you efficiently analyze all that data.

Tabular

The tabular sensitivity results consist of a list showing the least-cost **system** for each sensitivity case. In the example shown below, the first two columns display the values of the two sensitivity variables: the wind speed and the diesel fuel price. The next five columns contain icons indicating the presence in the least-cost system of the five components under consideration. From left to right, they are PV panels, wind turbines, the diesel generator, batteries, and the converter. Following are several columns that indicate the sizes and quantities of the components under consideration, plus a few summary values drawn from the simulation results of the least-cost system, such as the total capital cost, total net present cost, and levelized cost of energy.



Double click on a system below for optimization results.

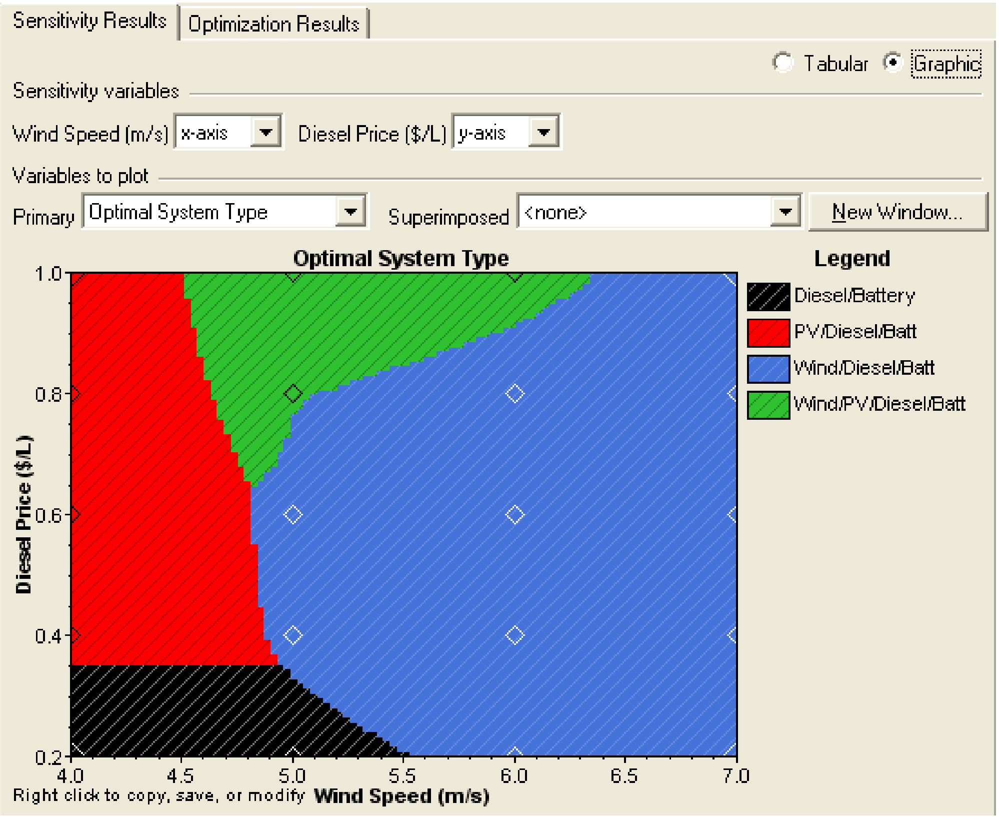
Wind (m/s)	Diesel ($/L)						PV (kW)	G3	Dsl (kW)	Batt.	Inv. (kW)	Disp. Strgy	Total Capital	Total NPC	COE ($/kWh)
4.000	0.20			✓	✓	✓			8	24	3	CC	$ 12,308	$ 67,117	0.345
4.000	0.40	✓		✓	✓	✓	1		8	24	3	CC	$ 19,308	$ 84,268	0.433
4.000	0.60	✓		✓	✓	✓	4		8	48	6	CC	$ 45,615	$ 106,088	0.545
4.000	0.80	✓		✓	✓	✓	4		8	48	6	CC	$ 45,615	$ 117,135	0.601
4.000	1.00	✓		✓	✓	✓	8		8	48	6	CC	$ 73,615	$ 126,538	0.650
5.000	0.20			✓	✓	✓			8	24	3	CC	$ 12,308	$ 67,117	0.345
5.000	0.40		✓	✓	✓	✓		1	8	24	3	CC	$ 25,508	$ 83,156	0.427
5.000	0.60		✓	✓	✓	✓		1	8	48	6	CC	$ 30,815	$ 104,154	0.535
5.000	0.80	✓	✓	✓	✓	✓	4	1	8	48	6	CC	$ 58,815	$ 113,628	0.583
5.000	1.00	✓	✓	✓	✓	✓	4	1	8	48	6	CC	$ 58,815	$ 120,890	0.621
6.000	0.20		✓	✓	✓	✓		1	8	24	3	CC	$ 25,508	$ 64,486	0.331
6.000	0.40		✓	✓	✓	✓		1	8	24	3	CC	$ 25,508	$ 75,536	0.388
6.000	0.60		✓	✓	✓	✓		2	8	48	6	CC	$ 44,015	$ 89,273	0.458
6.000	0.80		✓	✓	✓	✓		2	8	48	6	CC	$ 44,015	$ 95,629	0.491
6.000	1.00	✓	✓	✓	✓	✓	2	2	8	48	6	LF	$ 58,015	$ 101,056	0.519
7.000	0.20		✓	✓	✓	✓		1	8	24	3	CC	$ 25,508	$ 60,168	0.309
7.000	0.40		✓	✓	✓	✓		1	8	24	3	CC	$ 25,508	$ 69,749	0.358
7.000	0.60		✓	✓	✓	✓		2	8	48	6	LF	$ 44,015	$ 76,929	0.395
7.000	0.80		✓	✓	✓	✓		2	8	48	6	LF	$ 44,015	$ 80,308	0.412
7.000	1.00		✓	✓	✓	✓		2	8	48	6	LF	$ 44,015	$ 83,687	0.430

You can double click on any row in the table to jump to the **optimization results** for that sensitivity case. That lets you see the sub-optimal systems (the ones that were not least cost) and view the **simulation results** for any of the ranked systems.

Graphic

When the analysis involves more than one **sensitivity variable**, a graph often conveys the results in a more meaningful way than a table can. You can create three types of graphs: optimal system type charts, surface plots, and line graphs. These graphs are drawn right on the **Sensitivity Results** tab, but you can also create them in their own resizable windows by clicking the button labeled **New Window**. A right-click on any graph allows you to change its properties, copy it to the clipboard, or save it as an image file.

The optimal system type (OST) graph gives the highest-level view of the sensitivity results. It shows the least-cost type of system (diesel-battery is one type of system, wind-diesel-battery is another) versus two sensitivity variables. The example below shows the same information we just saw in the tabular display above. The graphic format makes it easier to see under which conditions the different types of systems are optimal. Diamonds indicate points where HOMER actually solved for the least-cost system. All other points are colored using interpolation.



○ Tabular ● Graphic

Sensitivity variables

Wind Speed (m/s) x-axis

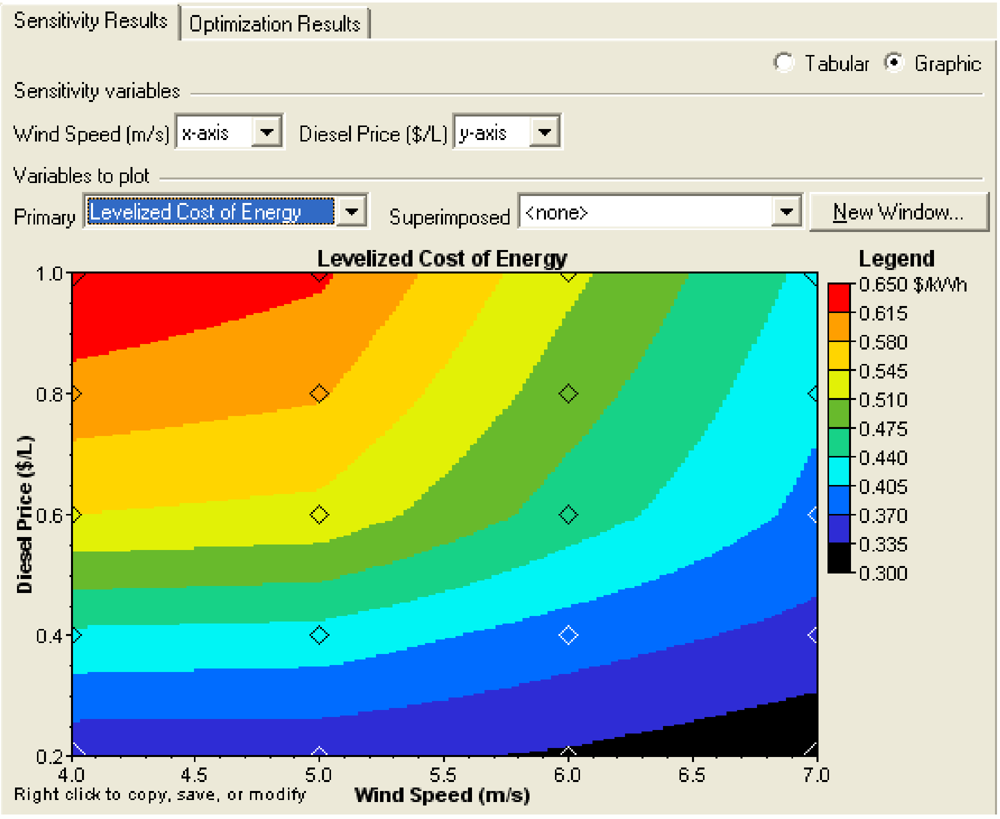
Diesel Price ($/L) y-axis

Variables to plot

Primary Optimal System Type

Superimposed <none>

If you choose to plot any variable other than the optimal system type versus two sensitivity variables, HOMER creates a surface plot. The example shown below plots the levelized cost of energy versus the same axes used in the optimal system type graph shown above. As in the OST graph, diamonds indicate points where HOMER actually solved for the least-cost system. The levelized cost of energy at all other points is inferred by interpolation.



○ Tabular ● Graphic

Sensitivity variables

Wind Speed (m/s) x-axis

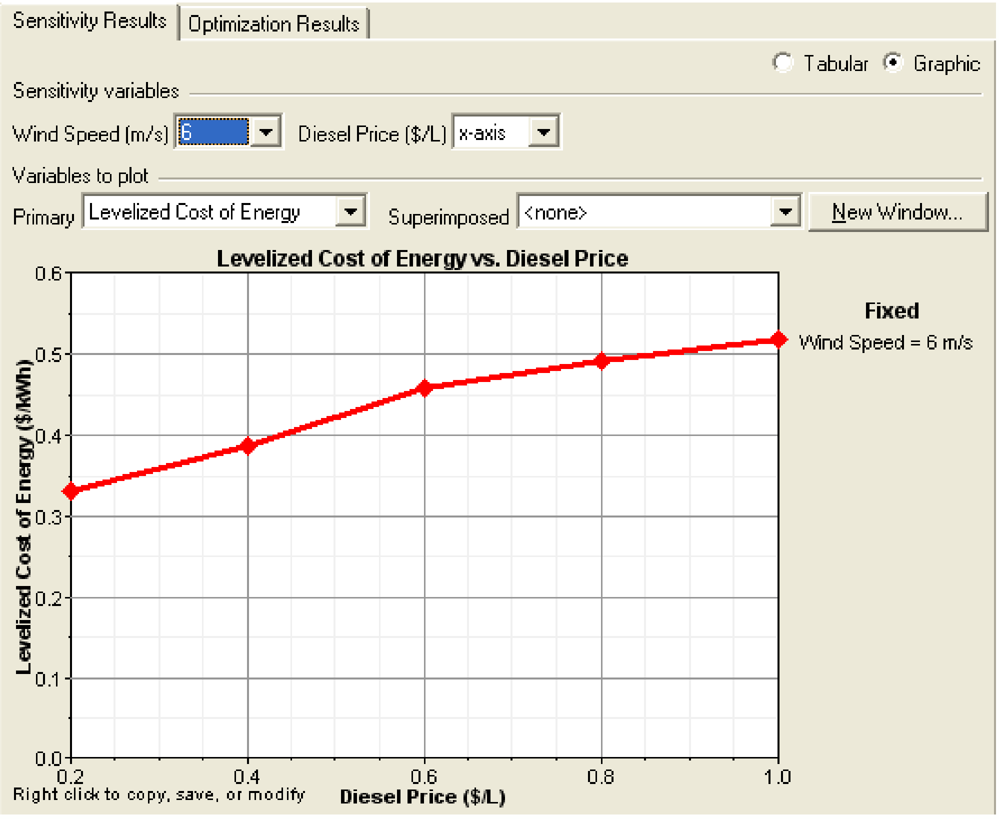
Diesel Price ($/L) y-axis

Variables to plot

Primary Levelized Cost of Energy

Superimposed <none>

HOMER creates line graphs to plot one output variable versus one single sensivity variable. The example shown below plots the levelized cost of energy versus the diesel fuel price. This is a subset of the results shown in the above surface plot, with the wind speed fixed at 6 m/s. The diamonds indicate points where HOMER actually solved for the least-cost system.



○ Tabular ● Graphic

Sensitivity variables

Wind Speed (m/s) 6

Diesel Price ($/L) x-axis

Variables to plot

Primary Levelized Cost of Energy

Superimposed <none>

Written by: Tom Lambert (**tom@homerenergy.com**)
Last modified: May 6, 2004

Simulation Results

Double click a row in the **optimization results** to open the simulation results window for that system. The top of the window displays the components of the system and three outputs: the total net present cost, levelized cost of energy, and operating cost.

This window contains the following tabs:

- The **Cost Summary** tab displays the total cash flow, categorized either by component or by cost type.
- The **Cash Flow** tab shows the year-by-year cash flows and provides access to the **detailed cash flow** table.
- The **Electrical** tab displays details about the production and consumption of electricity by the system.
- The **Thermal** tab shows details about the production and consumption of thermal energy by the system (if the system contains a thermal load).
- The **PV** tab shows details about the operation of the PV array if the system contains one.
- The **Wind Turbine** tab shows details about the operation of the wind turbine if the system contains one.
- The **Hydro** tab shows details about the operation of the hydro turbine if the system contains one.
- The **Generator** tab shows details about the operation of the generator if the system contains one.
- The **Grid** tab shows details about the purchases from and sales to the grid if the system is grid-connected, or about the **breakeven grid extension** if the system is not grid-connected.
- The **Battery** tab shows details about the use and expected lifetime of the battery.
- The **Converter** tab shows details about the operation of the inverter and rectifier, including capacity, electrical input and output, hours of operation, and losses.
- The **Emissions** tab displays the annual pollutants emitted by the system.
- The **Hourly Data** tab allows you to analyze those variables that are stored for each hour of the year.
- For a system with a hydrogen fuel cell, the FC tab displays fuel cell output. When the system includes an electrolyzer and storage tank, the **Hydrogen**, and **H2 Tank** tabs display hydrogen production and storage details respectively.

Written by: Tom Lambert (**tom@homerenergy.com**)
Last modified: June 5, 2008

System Control Inputs

Dispatch strategy

A **dispatch strategy** is a set or rules that govern the operation of the generator(s) and the battery bank. HOMER can model two dispatch strategies, cycle charging and load following. Which is optimal depends on many factors, including the sizes of the generators and battery bank, the price of fuel, the O&M cost of the generators, the amount of renewable power in the system, and the character of the renewable resources. If you choose to model both, HOMER will simulate each system using both dispatch strategies and you will be able to see which is optimal.

Under the **load following** strategy, whenever a generator is needed it produces only enough power to meet the demand. Load following tends to be optimal in systems with a lot of renewable power, when the renewable power output sometimes exceeds the load.

Under the **cycle charging** strategy, whenever a generator has to operate, it operates at full capacity with surplus power going to charge the battery bank. Cycle charging tends to be optimal in systems with little or no renewable power.

A **setpoint state of charge** can be applied to the cycle charging strategy. When a setpoint state of charge is applied, the generator(s) will not stop charging the battery bank until it reaches the specified state of charge. The sensitivity button to the right allows you to do a **sensitivity analysis** on this setpoint.

Note that the dispatch strategy is abbreviated "Disp. Strgy" in the sensitivity and optimization results tables.

Advanced

Allow systems with multiple generators	This check box controls whether HOMER considers systems that contain more than one generator. It has no effect if you are considering only one generator.
Multiple generators can operate simultaneously	This check box only affects the operation of systems that include two or more generators on the same bus. If you check this box, HOMER will allow multiple generators on the same bus to operate at once whenever necessary. Otherwise, multiple generators on the same bus must take turns operating.
Allow systems with generator capacity less than peak load	This check box controls whether HOMER will consider systems whose total generator capacity is less than the annual peak primary load.

Note that **Hybrid2** allows a great deal more flexibility in specifying the dispatch strategy than does HOMER. For more information on dispatch strategies for micropower systems, please see **Barley and Winn, 1996**.

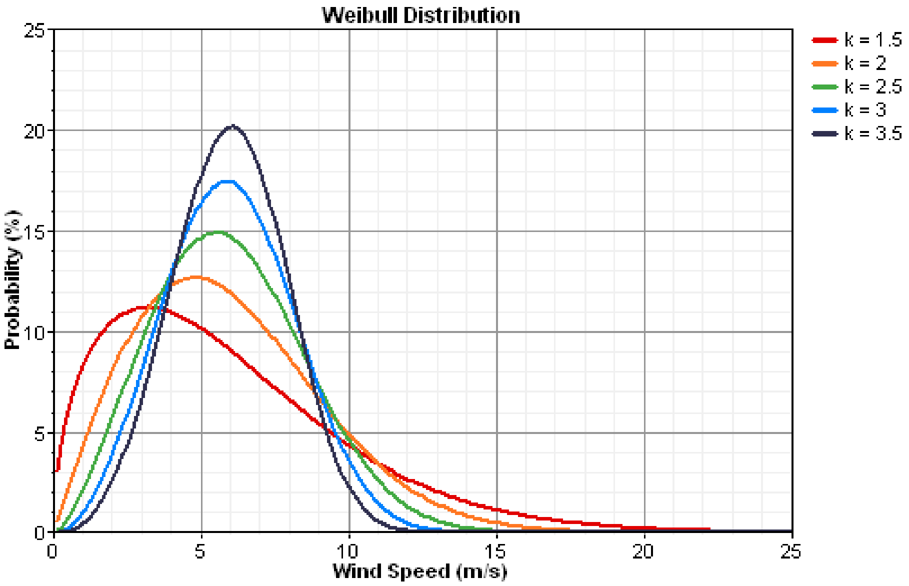
Written by: Tom Lambert (**tom@homerenergy.com**)
Last modified: October 29, 2004

Weibull *k* Value

Type: Input Variable
Units: none
Symbol: *k*
Typical Range: 1.5 - 2.5

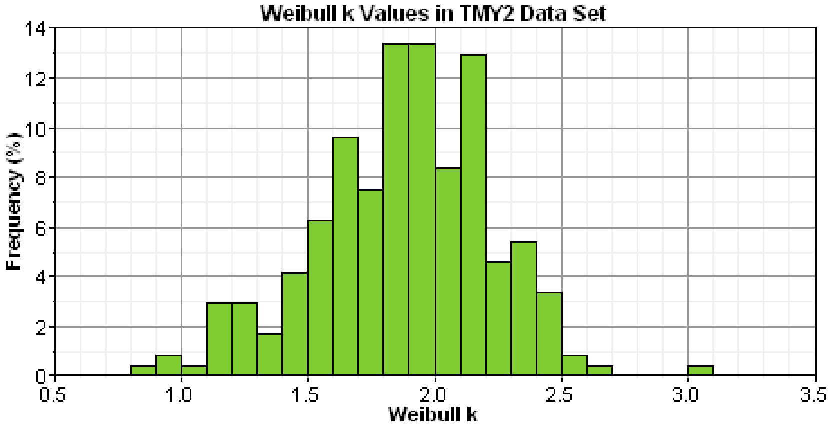
The Weibull *k* value, or Weibull shape factor, is a parameter that indicates the breadth of a distribution of wind speeds. HOMER fits a Weibull distribution to the wind speed data, and the *k* value refers to the shape of that distribution.

The graph below shows five Weibull distributions, all with the same average wind speed of 6 m/s, but each with a different Weibull *k* value. As the graph shows, lower *k* values correspond to broader distributions of wind speed, meaning that winds tend to vary over a large range of speeds. Higher *k* values correspond to narrower wind speed distributions, meaning that wind speeds tend to stay within a narrow range.

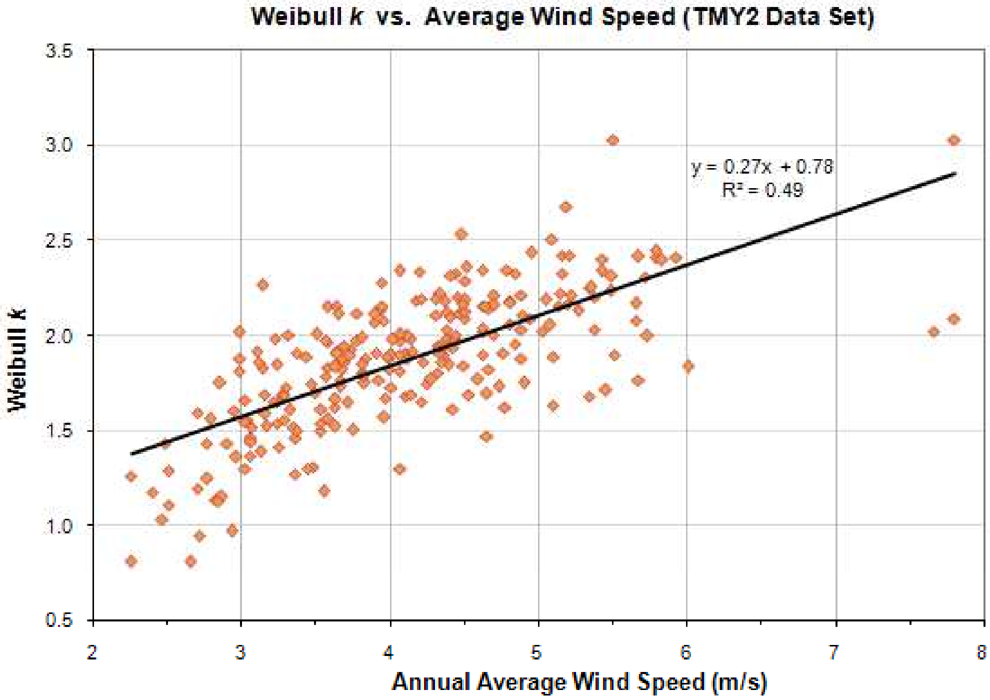


When fitting a Weibull distribution to measured wind data, HOMER uses the maximum likelihood method given by **Stevens and Smulders, 1979**.

To help HOMER users estimate Weibull *k* values in the absence of measured data, we calculated the best-fit Weibull *k* value for each of the 239 weather stations in the TMY2 data set. The histogram below shows the resulting distribution of Weibull *k* values. You can see the measured values themselves on the page containing the **table of measured wind parameters**.



There is some correlation between the Weibull k value and the average wind speed. In general, lower average wind speeds correspond to lower Weibull k values, and vice versa. The graph below shows Weibull k values versus annual average wind speeds taken from the **table of measured wind parameters**. Also shown on the graph is the linear least squares regression line.



See also

- **Weibull distribution**
- **Autocorrelation factor**
- **Diurnal pattern strength**
- **Hour of peak wind speed**
- **TMY2 wind parameters**

Written by: Tom Lambert (**tom@homerenergy.com**)
Last modified: April 11, 2008

Wind Resource Inputs

Use this window to describe the available wind resource. HOMER uses this data to calculate the output of the wind turbine each hour of the year.

If you are looking for wind data, see **Finding data to run HOMER**

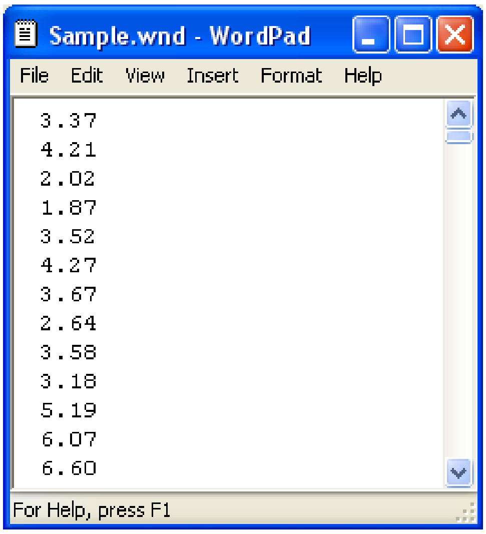
Baseline data

The baseline data is the set of 8,760 values representing the average wind speed, expressed in meters per second, for each hour of the year. HOMER displays the monthly averages calculated from the baseline data in the wind resource table and graph.

There are two ways to create baseline data: you can use HOMER to synthesize data, or you can import hourly data from a file.

To synthesize data, you must enter twelve average wind speed values: one for each month of the year. You can also edit the four advanced parameters Enter each month's average wind speed (m/s) in the appropriate row on the stream flow table. As you enter values in the table, HOMER builds a set of 8,760 values, or one wind speed value for each hour of the year. The synthesized data sequence has the specified seasonal and daily patterns, as well as the specified Weibull distribution and autocorrelation. For more information please see the article on **synthetic wind data**.

To import a file, you must have a text file that contains hourly wind speed data for a single year. Click **Import File** and open the text file. Although HOMER expects a text file with a '.wnd' extension, you can import a text file with any extension. The first few lines of a properly formatted .wnd file are shown below. Each of the 8,760 lines in the file should contain a value that represents the average wind speed (in m/s) over a single hour. The first line represents the wind speed between midnight and 1 a.m. on January 1, the second line between 1 a.m. to 2 a.m., and so on.



```
3.37
4.21
2.02
1.87
3.52
4.27
3.67
2.64
3.58
3.18
5.19
6.07
6.60
```

When you import data from a text file, HOMER makes a copy of the data set and integrates it with the HOMER (.hmr) file. Once the data is part of the HOMER file, HOMER no longer refers to the original text file. If you modify data in the original file, you must import the modified file in order for the modification to be included in the HOMER file. After you import a data file, HOMER calculates twelve monthly average wind speed values and displays them in the table and graph. HOMER also displays the name of the imported data file in the title of the stream flow graph. The four advanced parameters are also calculated from the imported data and displayed (read-only) in the text boxes.

If you click **Enter monthly averages** after importing data from a file, HOMER discards the data from the imported file and synthesizes new data based on the twelve monthly average wind speed values and four advanced parameters it calculated from the imported data. You can edit synthesized data by changing values in the monthly wind speed table. To edit values from an imported file, you must edit the file directly and then import the modified file, as described above.

Other parameters

Variable	Description
Altitude	The altitude in meters above sea level.
Anemometer height	The height above ground at which the wind speed data were measured.

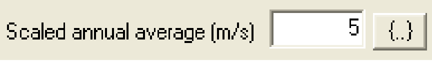
Click the **Variation With Height** button to bring up the **Wind Shear Inputs** window. In this window you specify how the wind speed changes with height above ground. HOMER uses this information to calculate the wind speed at the wind turbine's hub height, which may differ from the anemometer height.

Advanced parameters

Click on the links for detailed information on each of the following four advanced parameters.

Variable	Description
Weibull k	A measure of the long-term distribution of wind speeds.
Autocorrelation factor	A measure of the hour-to-hour randomness of the wind speed.
Diurnal pattern strength	A measure of how strongly the wind speed depends on the time of day.
Hour of peak wind speed	The time of day that tends to be windiest on average.

Scaled data for simulation


Scaled annual average (m/s) 5

HOMER uses scaled data for calculations. To create scaled data, HOMER multiplies each of the 8,760 baseline values by a common factor that results in an annual average value equal to the value that you specify in **Scaled annual average**. To determine the value of this factor, HOMER divides the scaled annual average by the baseline annual average. The scaled data retains the shape and statistical characteristics of the baseline data, but may differ in magnitude. The default value for the scaled annual average is the baseline annual average. When the two values are equal, the scaled data and baseline are identical. HOMER inteprets a scaled annual average of zero to mean that there is no wind resource.

Two reasons to use a scaled annual average that is different from the baseline annual average are for unit conversion or to perform a sensitivity analysis.

An example of using the scaled annual average for unit conversion is to convert data from an imported file that contains wind speed expressed in kilometers per hour. If the baseline annual average is 20 km/hr, you should enter 5.56 in **Scaled annual average**, so that the scaled data is equivalent to the baseline data, but expressed in m/s rather than km/hr: 1 m/s = 3.6 km/hr; 5.56 m/s = 20 km/hr.

Wind Shear Inputs

Use this window to describe the way the wind speed increases with height above ground. HOMER uses this information to calculate the wind speed at the hub height of the wind turbine.

Ground-level obstacles such as vegetation, buildings, and topographic features tend to slow the wind near the surface. Since the effect of these obstacles decreases with height above ground, wind speeds tend to increase with height above ground. This variation of wind speed with height is called *wind shear*. Wind energy engineers typically model wind shear using one of two mathematical models, the logarithmic profile or the power law profile.

Logarithmic profile

The logarithmic profile (or log law) assumes that the wind speed is proportional to the logarithm of the height above ground. The following equation therefore gives the ratio of the wind speed at hub height to the wind speed at anemometer height:

$$\frac{v(z_{hub})}{v(z_{anem})} = \frac{\ln\left(z_{hub}/z_0\right)}{\ln\left(z_{anem}/z_0\right)}$$

where:

z_{hub} = the hub height of the wind turbine [m]

z_{anem} = the **anemometer height** [m]

z_0 = the surface roughness length [m]

$v(z_{hub})$ = wind speed at the hub height of the wind turbine [m/s]

$v(z_{anem})$ = wind speed at anemometer height [m/s]

ln(..) = the natural logarithm

The surface roughness length is a parameter that characterizes the roughness of the surrounding terrain. The table below contains representative surface roughness lengths taken from **Manwell, McGowan, and Rogers**:

Terrain Description	z_0
Very smooth, ice or mud	0.00001 m
Calm open sea	0.0002 m
Blown sea	0.0005 m
Snow surface	0.003 m
Lawn grass	0.008 m
Rough pasture	0.010 m
Fallow field	0.03 m
Crops	0.05 m
Few trees	0.10 m
Many trees, few buildings	0.25 m
Forest and woodlands	0.5 m
Suburbs	1.5 m

City center, tall buildings	3.0 m

Power law profile

The power law profile assumes that the ratio of wind speeds at different heights is given by the following equation:

$$\frac{v(z_{hub})}{v(z_{anem})} = \left(\frac{z_{hub}}{z_{anem}}\right)^{\alpha}$$

where:

z_{hub} = the hub height of the wind turbine [m]

z_{anem} = the **anemometer height** [m]

α = the power law exponent

$v(z_{hub})$ = wind speed at the hub height of the wind turbine [m/s]

$v(z_{anem})$ = wind speed at anemometer height [m/s]

The power law exponent is a dimensionless parameter. Foundational research in fluid mechanics showed that its value is equal to 1/7 for turbulent flow over a flat plate. Wind speed researchers, however, have found that in practice the power law exponent depends on temperature, season, terrain roughness, and several other factors.

See also:

Wind resource inputs
Anemometer height
Wind turbine hub height

Written by: Tom Lambert (**tom@homerenergy.com**)
Last modified: August 11, 2004