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WHOLE LIFE SUSTAINABILITY ASSESSMENT AT THE BUILDING INDUSTRY AND CONSTRUCTED ASSETS, THROUGH THE WHOLE LIFE COSTING ASSESSMENT AND LIFE CYCLE COSTING ASSESSMENT EVALUATING THE ECONOMIC AND FINANCIAL ASPECTS

Alex Ximenes Naves

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Whole Life Sustainability Assessment at the Building Industry and Constructed Assets, through the Whole Life Costing Assessment and Life Cycle Costing Assessment evaluating the economic and financial aspects

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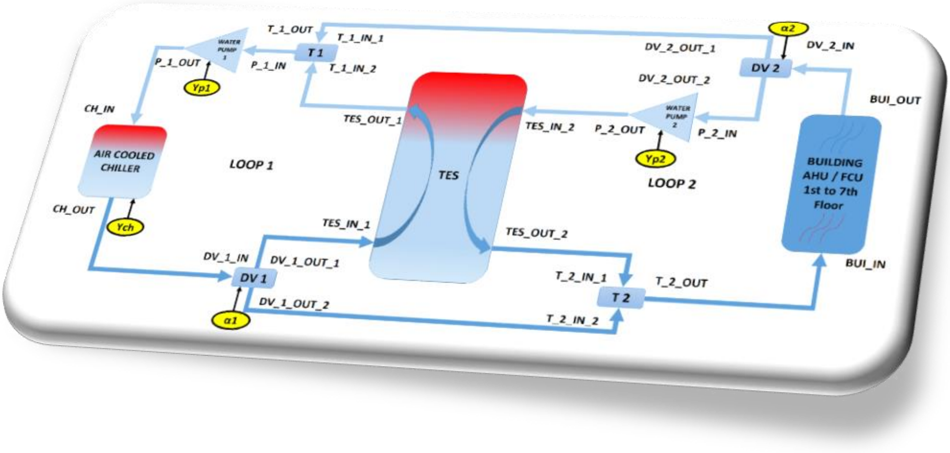
Alex Ximenes Naves



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Universidade Federal Fluminense

Department of Mechanical Engineering
Av. Països Catalans, 26 47007, Tarragona,
Spain

Postgraduate Program in Civil Engineering
Rua Passo da Patria, 156, Block D, Room 365
São Domingos, 24210-240, Niterói, RJ, Brazil

Dr. Assed Naked Haddad (Postgraduate Program in Civil Engineering, Universidade Federal Fluminense) and Dr. Dieter Thomas Boer (Department of Mechanical Engineering, Universitat Rovira I Virgili)

We state that the present study, entitled "Whole Life Sustainability Assessment at the Building Industry and Constructed Assets, through the Whole Life Costing Assessment and Life Cycle Costing Assessment evaluating the economic and financial aspects", presented by Alex Ximenes Naves for the award of the degree of Doctor, has been carried out under our supervision at the Department of Mechanical Engineering, Universitat Rovira i Virgili and the Postgraduate Program in Civil Engineering, Universidade Federal Fluminense.

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Doctoral Thesis Supervisors:

Dr. Dieter Thomas Boer

Dr. Assed Naked Haddad

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Summary

Net-zero energy buildings can be understood as buildings, that for a given time, generate as much energy as they consume. Either, from the point of view of supply or consumption, energy availability is related to some basic issues such as source (s), conversion, distribution, utilization, waste, optimization, efficiency and autonomy. These issues reveal the complexity of the subject of energy and justify the special attention given to it by the academic community.

To obtain tangible results in the analysis of these systems, in our study we focus on the modelling and optimization of energy solutions applied to buildings or similar systems. On the other hand, the time frame of the analysed objects was extended to their expected life cycle period.

The main objectives were stablished as: - Verify and analyse the state-of-the-art of renewable energy solutions for buildings and constructed assets and the applicability of life cycle costing analysis to these issues; - Configure reproducible models of buildings and their main electrical loads, via Computer Aided Process Engineering tools, to proceed simulations and optimization, considering as primary energy source solar energy; - Quantify, using real-life and hypothetical case studies, the benefits of the proposed solutions, aiming the whole life sustainability assessment through the reduction of the whole life cycle costing; and - Guarantee the reproducibility of the models and

main general results of this study and make them public, to contribute with their applicability and further researches.

A Literature Review was performed, focusing on Whole Life Costing Assessment (WLCA), that encompasses Life Cycle Costing Assessment (LCCA) and the adoption of this methodology for the economic pillar evaluation of the Sustainability Life Cycle in the Building and Solar Energy sectors.

Research showed the effectiveness of this methodology as the main component for assessing sustainability in the economic domain, and the relationship with the primary methods of environmental and social areas. The energy industry has been responsible for a significant number of publications, and the use of LCCA for different scale solar energy solutions as vehicles, houses, buildings, highways, rural properties and power plants indicates the usefulness of this methodology.

In the large-scale solar energy solutions, for Solar Photo Voltaic (SPV) and Concentrating Solar Power (CSP), the use of LCCA can upraise the advantages for choosing or integrating both solutions.

In minor scale solar energy solutions where the crescent technological evolution of SPV Cells has resulted in higher energy efficiency rates, the use of the LCCA can demonstrate the sensitive reduction on the Levelized Cost of Energy (LCOE), reflecting on the feasibility of solutions as the Net-Zero Energy Buildings (NZEB). Also clarifying the feasibility of their critical ancillary solutions, named

Electrical Energy Storages (EES) and the Thermal Energy Storages (TES).

These facts allied to the crescent number of studies and publications shows that LCCA is a promising field of studies and a powerful tool to achieve a most complete and reliable Life Cycle Sustainability Assessment of solar energy technologies and the solar energy implementation projects, mainly in the design phase. However, often the selected solar systems for buildings are analysed from an energetic and economic point of view rather than from detailed feasibility analysis and a life cycle perspective.

In the first case study, the objective was to evaluate with pre-design modelling and simulation the electrical demand of a Logistics Centre and determine the adequate system configurations, considering the Life Cycle Costing (LCC). The energy supplied by the photovoltaic (PV) panels connected with the grid brings more flexibility for energy management, and the energy surplus is an essential factor to be considered. A base case was established and three alternative scenarios for optimization considered.

Combining the use of TRNSYS 18 - Simulation Studio and its optimization library component, GenOpt - Generic Optimization Program, different options of grid energy contracts were simulated. They consider the variable tariffs and the integration with PV. Based on the LCC the GenOpt performed the Single-Objective Optimization (SOO) process, also considering the Payback Period (PBP) of investments.

This approach allowed envisaging possible configurations reducing up to a quarter of annual grid energy consumption and around 21% the LCC in a timeframe of 20 years. The PBP of investments is below six years. These results serve as input for the design and operation set up.

In the second case study, a hypothetical building was configured with detailed loads for tropical climate and systems to simulate different configurations of an air-cooled chiller associated with PV and TES. The objective was to show that the cooling systems, as one of the most energy consuming systems can have their efficiency increased if it is associated with photovoltaic panels (PV) and thermal energy storage systems (TES).

For tropical climate regions, the Brazilian National Energy Planning, PNE 2030 (Ministério de Minas e Energia 2006) indicates that the refrigeration and space cooling consumes a significant amount of energy, reaching 32% and 34% in residential and commercial buildings, doubling the contribution compared to the United States

Also using the TRNSYS 18 - Simulation Studio, a set of scenarios were simulated, and their outputs analysed in a life cycle perspective using Life Cycle Costing (LCC) for the calculations. The simulations considered variations in sizing and operability of the systems and generated results that establish a pathway toward a zero-energy building, using input data and parameter from manufacturers and standardized level of comfort for the building occupants to generate the feasible scenarios.

The modelling and simulation of different scenarios allowed envisage the most economic configurations for buildings in a life cycle perspective, though the LCC reduction within a safe range of operability considering the energy efficiency and consequently the sustainability aspects of buildings. The results can be used as premises for initial design or for planning retrofits of the buildings, aiming the zero-energy balance.

Resumo

Edifícios de energia resultante (ou líquida) nula podem ser entendidos como edifícios, que por um dado tempo, geram tanta energia quanto consomem. Seja do ponto de vista de oferta ou consumo, a disponibilidade de energia está relacionada a algumas questões básicas como fonte (s), conversão, distribuição, utilização, desperdício, otimização, eficiência e autonomia. Essas questões revelam a complexidade do tema energia e justificam a atenção especial dada pela comunidade acadêmica.

Para obter resultados tangíveis nesses estudos, seu escopo foi reduzido à modelagem e otimização de soluções energéticas aplicadas à indústria da construção, com foco em edificações. Por outro lado, o período de análise dos objetos analisados foi estendido para o período esperado do ciclo de vida.

Os principais objetivos destes estudos foram estabelecidos como: - Verificar e analisar o estado da arte das soluções de energia renovável para edifícios e ativos construídos e a aplicabilidade da análise de custos do ciclo de vida para estas questões; - Configurar modelos reprodutíveis de edifícios e suas principais cargas elétricas, via ferramentas de Engenharia de Processos Assistidos por Computador, para proceder a simulações e otimizações, em um nível de detalhamento que permitisse contemplar a sustentabilidade de soluções energéticas renováveis, com foco na fonte de energia primária; ; - Quantificar, usando estudos de casos reais e hipotéticos,

os benefícios das soluções energéticas estudadas, visando a avaliação da sustentabilidade do ciclo de vida, através da redução de todo o custo do ciclo de vida; e - Garantir a reprodutibilidade dos modelos e principais resultados gerais deste estudo além de torná-los públicos, para contribuir com sua aplicabilidade e futuras pesquisas.

Foi realizada uma Revisão da Literatura, com enfoque na Avaliação do Custo da Vida Total (WLCA), que engloba Avaliação do Custeio do Ciclo de Vida (LCCA) e adoção desta metodologia para avaliação do pilar econômico da Sustentabilidade do Ciclo de Vida nos setores de Construção e Energia Solar.

A pesquisa mostrou a eficácia desta metodologia como o principal componente para avaliar a sustentabilidade no domínio econômico, e a relação com os principais métodos das áreas ambiental e social. O setor de energia tem sido responsável por um número significativo de publicações, e o uso de LCCA para diferentes soluções de energia solar em escala como veículos, casas, edifícios, rodovias, propriedades rurais e usinas de energia indica a utilidade desta metodologia.

Nas soluções de energia solar em grande escala, tanto com Energia Solar Fotovoltaica (SPV) ou em Plantas para Concentração de Energia Solar (CSP), o uso de LCCA pode ajudar a evidenciar as vantagens ao escolher ou integrar ambas as soluções.

Em soluções de energia solar de pequena escala, onde a crescente evolução tecnológica das células SPV resultou em maiores taxas de eficiência energética, o uso do LCCA pode demonstrar a redução sensível no Custo Nivelado de Energia (LCOE), refletindo na viabilidade de soluções como o Edifícios com Balanço de Energia Zero (ZEB). Esclarecendo também a viabilidade de suas soluções auxiliares críticas, denominadas Armazenadores de Energia Elétrica (EES) e Armazenadores de Energia Térmica (TES).

Estes fatos aliados ao crescente número de estudos e publicações mostram que o LCCA é um campo promissor de estudos e uma poderosa ferramenta para alcançar uma Avaliação de Sustentabilidade do Ciclo de Vida mais completa e confiável de tecnologias de energia solar e projetos de implementação de energia solar, principalmente nos estágios iniciais dos projetos. No entanto, muitas vezes os sistemas solares selecionados para edifícios são analisados a partir de um ponto de vista energético e financeiro imediato, em vez de uma análise de viabilidade econômica detalhada com uma perspectiva de ciclo de vida.

No primeiro estudo de caso, o objetivo foi avaliar com modelagem pré-projeto e simulação a demanda elétrica de um Centro Logístico e determinar as configurações adequadas do sistema, considerando o Custo do Ciclo de Vida (LCC). A energia fornecida pelos painéis fotovoltaicos (PV) conectados à rede tras mais flexibilidade para o gerenciamento de energia, e o excedente de energia é um fator essencial a ser considerado. Um caso base foi estabelecido e outros três cenários alternativos, para otimização.

Combinando o uso do TRNSYS 18 – Ambiente de Simulação e seu componente de otimização, o GenOpt - Programa de Otimização

Genérica, foram simuladas diferentes opções de contratos de energia da rede, considerando as tarifas variáveis e a integração com o VP. Baseado no LCC, o GenOpt executou o processo de Otimização de Função Objetiva Única (SOO), considerando também o Período de Tempo para Compensação (PBP) do investimento.

Essa abordagem permitiu visualizar possíveis configurações reduzindo até um quarto do consumo anual de energia da rede e cerca de 21% do LCC em um período de 20 anos. O PBP dos investimentos foi inferior a seis anos. Esses resultados são úteis para a fase de análise de viabilidade dos projetos ou configuração da operação.

No segundo estudo de caso, um edifício hipotético foi configurado com cargas e sistemas detalhados para simular diferentes configurações de um Ar Condicionado resfriado a ar associado a PV e TES. O objetivo foi mostrar que os sistemas de refrigeração, para edifícios localizados em clima tropical, como um dos sistemas de maior consumo de energia, podem ter sua eficiência aumentada se associados a painéis fotovoltaicos (PV) e sistemas de armazenamento de energia térmica (TES).

Para as regiões de clima tropical, pode-se identificar a partir do Planejamento Nacional de Energia, PNE 2030 (Ministério de Minas e Energia 2006), que a refrigeração e o resfriamento de espaços representam uma parcela significativa do consumo de energia, chegando a 32% em edifícios residenciais e 34% nos comerciais, cerca de duas vezes do consumo relativo nos Estados Unidos.

Também usando o TRNSYS 18 – Ambiente de Simulação, um conjunto de cenários foi simulado e suas saídas analisadas em uma perspectiva de ciclo de vida usando o LCC para os cálculos.

As simulações consistiram em variações no dimensionamento e na operacionalidade dos sistemas e geraram resultados que validam uma proposta de edifício de energia zero, usando dados de entrada e parâmetros dos fabricantes e nível padronizado de conforto para os ocupantes do edifício para gerar os cenários viáveis.

A modelagem e simulação de diferentes cenários permitiu visualizar as configurações mais econômicas para edifícios em uma perspectiva de ciclo de vida, com a redução de LCC dentro de uma faixa de operação segura considerando a eficiência energética e consequentemente os aspectos de sustentabilidade dos edifícios. Os resultados podem ser utilizados como premissas para o projeto inicial ou para o planejamento de retrofits de edifícios, visando o balanço de energia zero.

Resumen

Los edificios de energía resultante nula se pueden entender como edificios, que por un tiempo dado generan tanta energía como consumen. Desde el punto de vista de oferta o consumo, la disponibilidad de energía está relacionada con algunas cuestiones básicas como fuente (s), conversión, distribución, utilización, desperdicio, optimización, eficiencia y autonomía. Estas cuestiones revelan la complejidad del tema de la energía y justifican la atención especial dada por la comunidad académica.

Para obtener resultados tangibles en estos estudios, su alcance fue reducido al modelado y optimización de soluciones energéticas aplicadas a la industria de la construcción, con foco en edificaciones. Por otro lado, el período de análisis de los objetos analizados fue extendido para el período esperado del ciclo de vida.

Los principales objetivos de estos estudios se establecieron como: - Verificar y analizar el estado del arte de las soluciones de energía renovable para edificios y activos construidos y la aplicabilidad del análisis de costos del ciclo de vida para estas cuestiones; - Configurar modelos reproducibles de edificios y sus principales cargas eléctricas, a través de herramientas de ingeniería de procesos asistidos por ordenador, para proceder a simulaciones y optimizaciones, a un nivel de detalle que permitiera contemplar la sustentabilidad de soluciones energéticas renovables, con foco en la fuente de energía primaria; - Cuantificar, utilizando estudios de casos

reales e hipotéticos, los beneficios de las soluciones energéticas estudiadas, buscando la evaluación de la sostenibilidad del ciclo de vida, a través de la reducción de todo el costo del ciclo de vida; y - Garantizar la reproducibilidad de los modelos y principales resultados generales de este estudio además de hacerlos públicos, para contribuir con su aplicabilidad y futuras investigaciones.

Se realizó una Revisión de la Literatura, con enfoque en la Evaluación del Costo de la Vida Total (WLCA), que engloba la Evaluación del Costeo del Ciclo de Vida (LCCA) y la adopción de esta metodología para la evaluación del pilar económico de la Sostenibilidad del Ciclo de Vida en los sectores de Construcción y Energía Solar.

La investigación mostró la eficacia de esta metodología como el principal componente para evaluar la sostenibilidad en el ámbito económico, y la relación con los principales métodos de las áreas ambiental y social. El sector de energía ha sido responsable de un número significativo de publicaciones, y el uso de LCCA para diferentes soluciones de energía solar a escala como vehículos, casas, edificios, carreteras, propiedades rurales y plantas de energía indica la utilidad de esta metodología.

En las soluciones de energía solar a gran escala, tanto con la energía solar fotovoltaica (SPV) o en las plantas para la concentración de energía solar (CSP), el uso de LCCA puede ayudar a evidenciar las ventajas al elegir o integrar ambas soluciones.

En las soluciones de energía solar de pequeña escala, donde la creciente evolución tecnológica de las células SPV resultó en mayores tasas de eficiencia energética, el uso del LCCA puede demostrar la reducción sensible en el Costo Nivelado de Energía (LCOE), reflejando la viabilidad de soluciones como el Edificios con Balance de Energía Cero (ZEB). Aclarando también la viabilidad de sus soluciones auxiliares críticas, denominadas Almacenadores de Energía Eléctrica (EES) y Almacenadores de Energía Térmica (TES).

Estos hechos aliados al creciente número de estudios y publicaciones muestran que el LCCA es un campo prometedor de estudios y una poderosa herramienta para alcanzar una Evaluación de Sostenibilidad del Ciclo de Vida más completa y confiable de tecnologías de energía solar y proyectos de implementación de energía solar, principalmente en las etapas iniciales de los proyectos. Sin embargo, a menudo los sistemas solares seleccionados para edificios se analizan desde un punto de vista energético y financiero inmediato, en lugar de un análisis de viabilidad económica detallada con una perspectiva de ciclo de vida.

En el primer estudio de caso, el objetivo fue evaluar con modelado pre-proyecto y simulación la demanda eléctrica de un Centro Logístico y determinar las configuraciones adecuadas del sistema, considerando el Costo del Ciclo de Vida (LCC). La energía suministrada por los paneles fotovoltaicos (PV) conectados a la red tras más flexibilidad para la gestión de energía, y el excedente de energía es un factor esencial a ser considerado. Se ha establecido un caso base y otros tres escenarios alternativos para la optimización.

Al combinar el uso del TRNSYS 18 - Ambiente de Simulación y su componente de optimización, el GenOpt - Programa de Optimización Genérica, se simularon diferentes opciones de contratos de energía de la red, considerando las tarifas variables y la integración con el VP. Basado en el LCC, GenOpt ejecutó el proceso de Optimización de Función Objetiva Única (SOO), considerando también el Período de Tiempo para Compensación (PBP) de la inversión.

Este enfoque permitió visualizar posibles configuraciones reduciendo hasta un cuarto del consumo anual de energía de la red y cerca del 21% del LCC en un período de 20 años. El PBP de las inversiones fue inferior a seis años. Estos resultados son útiles para la fase de análisis de viabilidad de los proyectos o la configuración de la operación.

En el segundo estudio de caso, un edificio hipotético fue configurado con cargas y sistemas detallados para simular diferentes configuraciones de un aire acondicionado enfriado por aire asociado a PV y TES. El objetivo fue mostrar que los sistemas de refrigeración, para edificios ubicados en clima tropical, como uno de los sistemas de mayor consumo de energía, pueden tener su eficiencia aumentada si se asocian a paneles fotovoltaicos (PV) y sistemas de almacenamiento de energía térmica (TES) .

Para las regiones de clima tropical, se puede identificar a partir de la Planificación Nacional de Energía, PNE 2030 (Ministerio de Minas y Energía 2006), que la refrigeración y el enfriamiento de espacios representan una parte significativa del consumo de energía, llegando a 32 % en edificios residenciales y el 34% en los comerciales, cerca de dos veces del consumo relativo en los Estados Unidos.

También utilizando el TRNSYS 18 - Entorno de Simulación, un conjunto de escenarios fue simulado y sus salidas analizadas en una perspectiva de ciclo de vida usando el LCC para los cálculos.

Las simulaciones consistieron en variaciones en el dimensionamiento y la operatividad de los sistemas y generaron resultados que validan una propuesta de edificio de energía cero utilizando datos de entrada y parámetros de los fabricantes y nivel estandarizado de confort para los ocupantes del edificio para generar los escenarios viables.

El modelado y simulación de diferentes escenarios permitió visualizar las configuraciones más económicas para edificios en una perspectiva de ciclo de vida, con la reducción de LCC dentro de un rango de operación segura considerando la eficiencia energética y consecuentemente los aspectos de sustentabilidad de los edificios. Los resultados pueden ser utilizados como premisas para el proyecto inicial o para la planificación de retrofits de edificios, buscando el balance de energía cero.

Contents

Abbreviations and Nomenclature

BESS	Battery Energy Storage System
BS ISO	British Standards – International Standards Organization
CIGS	Solar Cells compound in Copper Indium Gallium Selenide (Cu, I, Ga and Se)
cLCC	Conventional LCC or Financial LCC
CSP	Concentrating Solar Power
DfD	Design for Disassembly
DfE	Design for Environment
DJSI	Dow Jones Sustainability Index
DNI	Direct Normal Irradiance
EC	European Commission
ECM	Energy Conservation Measures
EES	Electrical Energy Storage
eLCA	Environmental LCC
eLCC	Environmental LCC
EOL	End of Life
EPBD	Energy Performance of Buildings Directive

feLCC	Full Environmental LCC
FEMP	Federal Energy Management Program
fLCC	Financial LCC or Conventional LCC
GHG	Green House Gas
GSHP	Ground Source Heat Pump
HPVT	Hybrid Photovoltaic Thermal
HVAC	Heating, Ventilation, Air Conditioning
IEA	International Energy Agency
IISD	International Institute for Sustainable Development
IPP	Integrated Product Policy
ISO	International Standards Organization
LCA	Life Cycle Assessment
LCC	Life Cycle Cost or Life Cycle Costing
LCCA	Life Cycle Cost Assessment or Life Cycle Cost Analysis
LCE	Life Cycle Engineering
LCOE	Levelled Cost of Energy
LCSA	Life Cycle Sustainability Assessment
MTCDE	Metric Tons of Carbon Dioxide Equivalent
NIST	National Institute of Standards and Technology

NPV	Net Present Value
NREL	National Renewable Energy Laboratory - USA
NZEB	Net Zero Energy Building (NREL)
nZEB	Nearly Zero Energy Building (European Commission)
OPV	Organic Photo Voltaic
PCM	Phase Change Materials
PTC	Parabolic Through Collector
PV	Photovoltaic
PVT	Photovoltaic Thermal
SETAC	Society of Environmental Toxicology and Chemistry
sLCA	Social LCA
sLCC	Social LCC
SPV	Solar Photo Voltaic
SPVT	Solar Photo Voltaic and Thermal
TCO	Total Cost of Ownership
TES	Thermal Energy Storage
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
WCDE	World Commission on Environment and Development

WERF	Water Environment Research Foundation

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Scientific Production

1. Published Articles

Authors: Naves, Alex Ximenes; Camila Barreneche; A Inés Fernández; Luisa F Cabeza; Assed Naked Haddad and Dieter Boer.
Year: 2018
Title: "Life Cycle Costing as a Bottom Line for the Life Cycle Sustainability Assessment in the Solar Energy Sector: A Review."
Journal: Solar Energy
doi:10.1016/j.solener.2018.04.011.

2. eBook Chapter

Authors: Naves, Alex Ximenes; Dieter Boer and Assed Naked Haddad.
Year: 2017
Title: "Revisão do Custeio no Ciclo de Vida na Indústria da Construção como um requisito para a Avaliação da Sustentabilidade no Ciclo de Vida"
eBook: V CREA-RJ Prize 2016 (Brazil)
https://novoportal.crea-rj.org.br/premiocrea/publicacoes/2016
https://issuu.com/crea-rj9/docs/ebook_v_premio (pg. 55-56)

3. Submitted Articles

Authors: Naves, Alex Ximenes Naves; Victor Tulus; Assed Naked Haddad; Laureano Jimenez and Dieter Boer.
Year: 2019
Title: "Grid-Integrated PV Modelling and Simulation 2 applied to Energy Efficiency Optimization in the 3 Industrial Sector: A Logistics Center Case Study"
Journal: Applied System Innovation

4. Papers in progress

Authors: Naves, Alex Ximenes Naves; Assed Naked Haddad and Dieter Boer.
Year: 2019 (to be submitted on July)

Title: “Integration of renewable energy and thermal energy storage in residential buildings”
Journal: Energies

5. Conferences

Authors: Alex Ximenes Naves; Victor Tulus; Assed Naked Haddad; Laureano Jimenez; Luisa F. Cabeza and Dieter Boer.
Yea: 2019
Title: “Simulation and optimization of a grid-integrated PV: A logistics center case study”
Congress: XI National and II International Congress on Thermodynamics Engineering, UCLM
Country: Spain

Authors: Alex Ximenes Naves; Mohamed Abokersh; Victor Tutus; Assed Naked Haddad; Luisa F. Cabeza and Dieter Boer.
Year: 2019
Title: “Integration of Photovoltaics in the Industry Sector under Flexible Electricity Tariffs”
Congress: ISES Solar World Congress 2019
Country: Chile

Authors: Alex Ximenes Naves; Ahmed Mostafa Abdelmoaty; Alba Torres-Rivas; Mariana Palumbo; Assed Haddad; Luisa Cabeza; Laureano Jimenez and Dieter Boer.
Year: 2018
Title: “Energy Efficiency Optimization of Cooling Systems Using Thermal Energy Storage: Towards Zero Energy Balance in Buildings”
Congress: 1st SDEWES Latin American Conference on sustainable Development of Energy, Water and Environmental Systems
Country: Brazil

Authors: Alba Torres-Rivas; Alex Ximenes Naves; Mariana Palumbo; Assed Naked Haddad; Laureano Jimenez; Luisa Cabeza and Dieter Boer.
Year: 2018
Title: “Low impact building insulation materials: Modelling of condensation risk in different climates”

Congress: 1st SDWES Latin American Conference on sustainable Development of Energy, Water and Environmental Systems
Country: Brazil

Authors: Alex Ximenes Naves; Mariana Palumbo; Luisa F. Cabeza; Dieter Boer and Assed Naked Haddad.
Year: 2017
Title: "Life cycle costing and risk management in the construction industry: review and implications"
Congress: ICEUBI 2017, International Congress on Engineering, University of Beira Interior
Country: Portugal

Authors: Mohammad Najjar; Karoline Figueiredo; Alex Ximenes Naves; Dieter Boer and Assed Naked Haddad
Year: 2017
Title: "Evaluation of environmental impacts of building materials in the construction sector integrating BIM and LCA"
Congress: ICEUBI 2017, International Congress on Engineering, University of Beira Interior
Country: Portugal

6. Author's profiles

ORCID: 0000-0001-7768-9932
https://orcid.org/0000-0001-7768-9932

WEB OF SCIENCE RESEARCHER ID: B-4631-2018
https://publons.com/researcher/1982540/alex-x-naves

SCOPUS ID: 57201822384
https://www.scopus.com/authid/detail.uri?authorId=57201822384

I - Introduction

1. Background and Motivation

A traditional key principle of the economics states that the value of the demanded goods is directly proportional to their scarcity. Even at different technological development stages of the society, the energy consumed on the human activities can be considered a fundamental resource, and its scarcity make energy one of the most valuable resource around the world.

From the point of view of supply or consumption, energy availability is related to some basic issues such as source (s), conversion, distribution, utilization, waste, optimization, efficiency and autonomy. These issues reveal the complexity of the subject of energy and justify the special attention given to it by the academic community, both economically and technically.

Concerning sources and conversion aspects, Nakićenović et al. (Nakićenović, Gilli, and Kurz 1996) in their studies, remind an important background. They distinguish primary energy as the energy that is embodied in resources as they exist in nature as the chemical energy embodied in fossil fuels (coal, oil, and natural gas) or biomass, the potential kinetic energy of water drawn from reservoirs, the electromagnetic energy of solar radiation, and the energy released in nuclear reactions. Secondary energy comes from the conversion and transforming of primary energy in electricity and fuels such as gasoline, jet fuel, or heating oil and serve as energy carriers for subsequent energy conversions or market transactions.

On the demand side, concerning the consumption aspects, according to the Global Energy Assessment Report (Ürge-Vorsatz et al. 2012), in 2010, the end-user services in buildings of United States were responsible for 41% of primary energy consumption, 22% in the residential buildings and 19% in the commercial ones. This consumption is followed by the industry and transportation sectors, with 31% and 28%, respectively. At this scenario, the consumption breakdown in Figure 1 shows that space cooling is responsible for 14% and 15% of energy consuming at the US commercial and residential buildings, respectively.

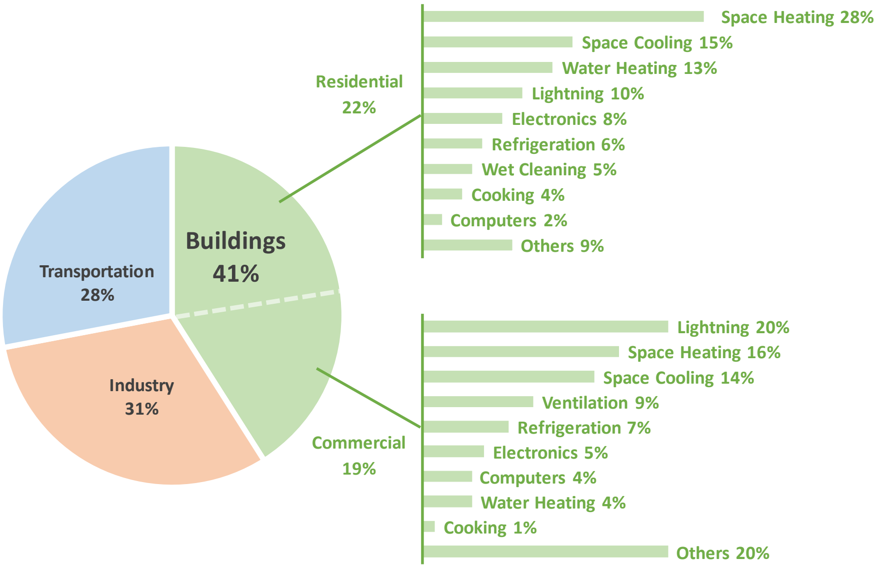


Figure 1 - Energy use in the US residential and commercial buildings in 2010, and the consumption breakdown (Ürge-Vorsatz et al. 2012)

For tropical climate regions, can be depicted from the Brazilian National Energy Planning, PNE 2030 (Ministério de Minas e Energia 2006), the share of electrical energy consumption for end-user services in buildings, compared to industry and transportation shown in Figure 2. The refrigeration and space cooling consume a significant amount of that energy, reaching 32% and 34% in residential and commercial buildings, about twice of the relative consumption in United States (see Figure 1).

These breakdowns made in the Brazilian Useful Energy Balance (Ministério de Minas e Energia 2005) of the electrical energy consumption are an evidence that space cooling is one of the energy services to be studied and improved in residential buildings in Brazil, towards the energy efficiency, associating, for example, chiller solutions and TES.

The cooling demand, concentrated in the hours of most solar incidence, increase the energy consumption of the buildings in a period of the day were the higher tariffs are charged by the electricity suppliers. Allied to this, the high gaps of temperature to be compensated to guarantee the thermal comfort, causes a performance decrease of the cooling systems, resulting in more energy consumption.

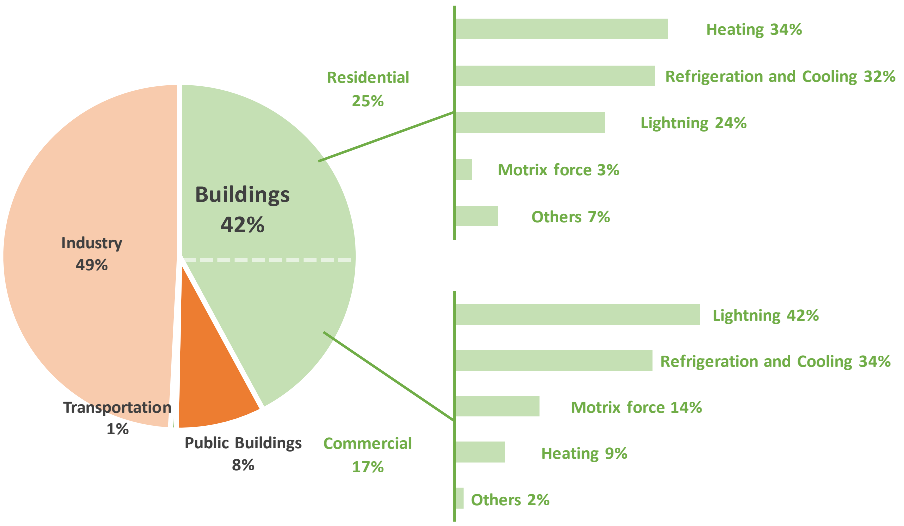


Figure 2 - Energy use in Brazilian residential and commercial buildings in 2015 (EPE 2016), and the consumption breakdown (Ministério de Minas e Energia 2005)

Besides cooling, and considering the lightning consumption, also shown in Figure 2, the amount of energy for these two loads goes to 56% and 76% at the residential and commercial buildings, respectively. If the heating consumption is considered, the consumption shares of these three loads, goes to 90% and 85%, respectively, evidencing that PV associated with the grid has an attractive potential, either for supply the partial chiller energy demand or the lightning and heating demands.

It is important to observe that the share of energy consumption for heating, mainly in residential buildings, highlights the potential of the thermal solar panels as a significant energy efficiency factor and in part could justify the increasing number of published studies, detected on the literature review, related to cogeneration, that is, the physical integration of photovoltaic and thermal solar collectors into hybrid solar panels (PVT).

The Premises and Guidelines for the Brazilian National Energy Efficiency Planning (Ministério de Minas e Energia 2011), corroborates this approach for residential buildings when points out the potential of energy efficiency initiatives related to that energy used to maintain the customer's comfort.

The Energy Efficiency has been taken as one of the most feasible initiatives to mitigate the impact of energy consumption. This approach also give information to analyse the feasibility of Energy Autonomy for buildings or their expansion to neighbourhoods, as discussed by Mckenna et al. (Mckenna, Merkel, and Fichtner 2017) ,that could be considered a step beyond the Zero Energy Buildings (Marszal et al. 2012a)(Cellura et al. 2014).

The primary energy source based on electromagnetic energy of solar radiation, named solar energy, was adopted as the main renewable energy resource.

2. Objectives

To obtain tangible results in this study, its scope was narrowed to the modelling and optimization of energy solutions applied to the construction industry, focusing on buildings. On the other hand, the time frame of the analysed objects was extended to their expected life cycle period.

The main objectives of this study are:

- Verify and analyse the state-of-the-art of renewable energy solutions for buildings and constructed assets and the applicability of life cycle costing analysis to these issues;
- Configure reproducible models of buildings and their main electrical loads, via Computer Aided Process Engineering tools, to proceed simulations an optimization, in a level of detail that allowed to envisage the sustainability of energy renewable solutions, focusing on the primary energy source, solar energy;
- Quantify, using real-life and hypothetical case studies, the benefits of the studied energy solutions, aiming the whole life sustainability assessment through the reduction of the whole life cycle costing;
- Guarantee the reproducibility of the models and main general results of this study and make them public, to contribute with their applicability and further researches.

The steps adopted as guidelines to the modelling of the energy solutions were based on the framework showed in Figure 3.

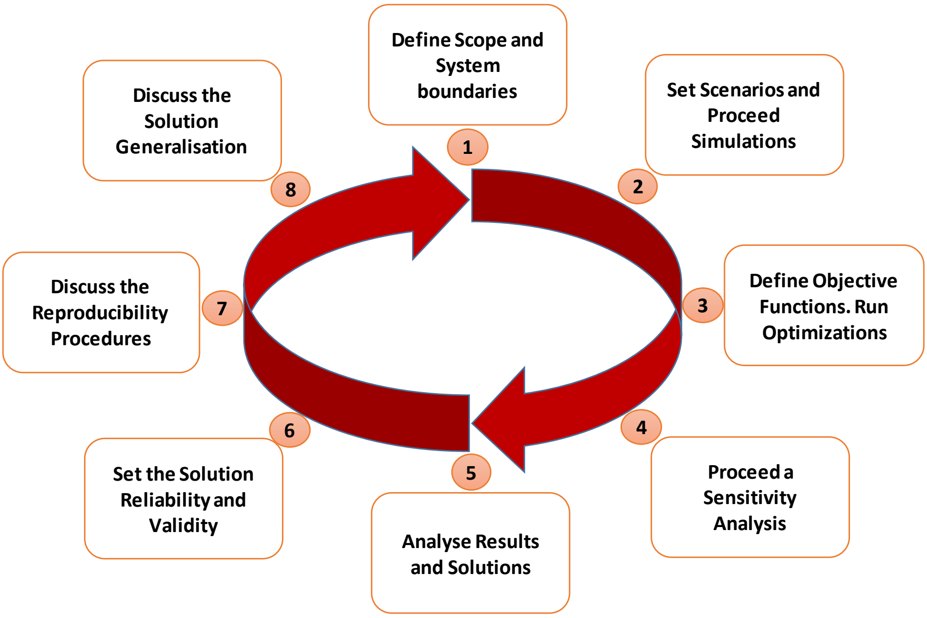


Figure 3 - General framework for energy efficiency analysis

3. Methodology

3.1. Literature Review

For the literature review, the Scopus Elsevier Database was the primary source for retrieving articles and books. The refinement of LCC and WLC definitions came mainly from the Society of Environmental Toxicology and Chemistry (SETAC) and the standards issued by the International Standards Organization (ISO), the British Standards Institute (BSI), and the American Society for Testing and Materials (ASTM).

To evidence of the relationship between LCC, WLC and Solar Energy were conducted searches in both issues separately and further on in conjunction. For the Solar Energy issue, after verifying the vast amount of information contained in the Scopus Database (almost 94 thousand documents), were done successive refinements. For the LCC and WLC issue were tracked the same steps (initially almost 8 thousand documents). This approach is practical and has support on publications of bibliometric and bibliographic specialist authors as Rowley and Frances (Rowley and Frances S 2012).

3.2. Bibliometric Analysis

The Bibliometric Software VosViewer (Nees Jan van Eck; Ludo Waltman 2015) that has smooth integration with the Scopus Elsevier Database was used to guide the Literature Review steps and allowed, for example, analyse 4 thousand keywords and 11 thousand terms from Titles and Abstracts at the same time and categorise them, based on their relevance or occurrence. The documents were downloaded from Scopus in a comma separated format to VosViewer, to compose the clusters aiming to categorise the documents and identify the main issues discussed, its relatedness and the primary sources.

3.3. Modelling, simulation and optimization

Due to the characteristics of the object of study, mainly because of the existence of a great number of independent variables, the use of equations relating the systems variables has an excessive computational time consuming. However, the use of simulation software based on numerical calculation of models of well know systems (e.g. buildings and its facilities) allows the analysis of these models. By these reasons, the modelling for simulations was built using TRNSYS18 - Simulation Studio (University of Wisconsin-Madison 2004) and the metaheuristic algorithm based on particle swarm was performed by its optimization library component, GenOpt - Generic Optimization Program (Wetter 2011). The modelling of the scenarios in TRNSYS 18 uses modules, named types, which represents the main systems.

For the energy efficiency studies, three models were configured and integrated at TRNSYS 18. The integration is a prerequisite to run the optimizations of the complete model by GenOpt.

The first model, based on the TRNSYS Type 56b, consists in a hypothetical Building Model designed to obtain the electrical energy demand based on three main loads, that is, the lightning, equipment and cooling energy demand. The lightning and equipment demand are obtained directly from the Building Model, based on the configured characteristics and the occupation schedule of the units. The cooling electrical energy demand, necessary to maintain the thermal comfort of the occupants, generated by the cooling system, is obtained through the cooling energy demand, used as input to the second model. This demand is based on the building intrinsic characteristics, the lightning, equipment and occupants loads, adjusted to the occupation profiles and the weather conditions.

A second model, compound by the Chiller and TES, use as input the cooling energy demand obtained from the Building Model. This model allows to obtain detailed data from each of the ASHRAE operational modes and calculates the cooling electrical energy demand for the operational modes during the optimization process.

The third model, represented by the PV/GRID Model, was designed to allow the simulations and optimizations of the different configurations of PV and GRID as the supply of electrical energy, considering the three main loads electrical demand obtained from the other two TRNSYS models. A module type 9c is the integration point between this model and the other two models, reading the electrical energy demand from the building.

The results of modelling, simulation and optimization, according to the flowchart described in Figure 4, can support an eventual design phase of the feasible solutions and foreseen advantages, disadvantages, restrictions and opportunities with technological and economic aspects in a life cycle approach.

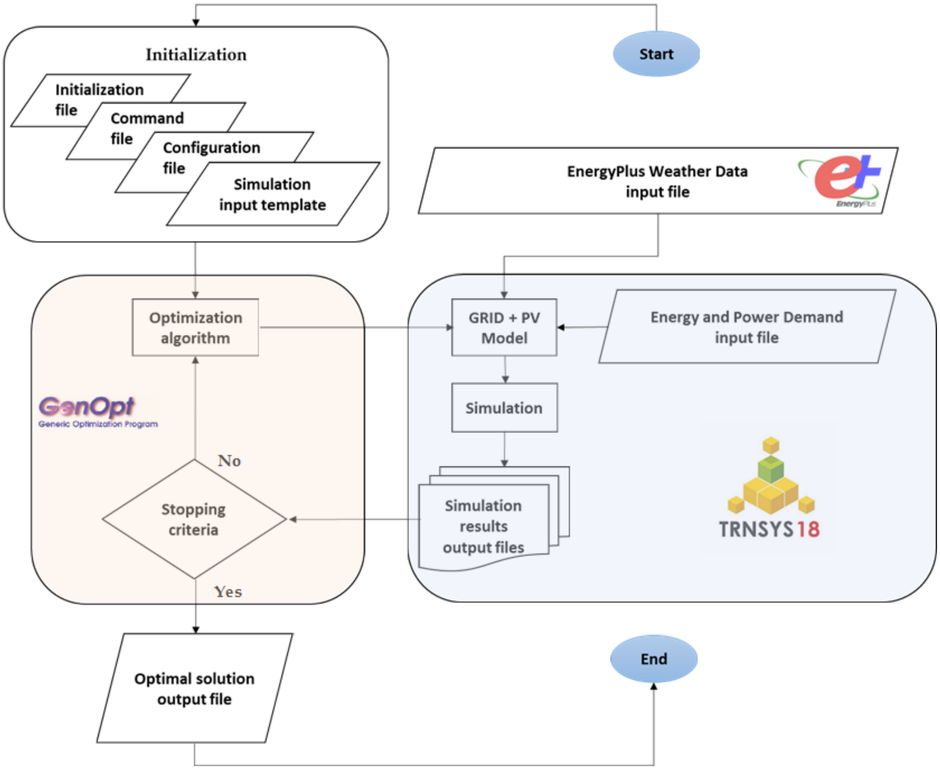


Figure 4 - Flowchart of modelling and simulation steps.

3.4. Whole Life Costing and Life Cycle Costing

The LCC basic calculation formulas are presented in the publications of the American Society for Testing and Materials (ASTM E0917 2015a) and are summarised in the Equations 2, 3, 4 and 5. The Present Value of LCC, named PVLCC, can be calculated as follows:

$$PVLCC\ (t, i, C) = \sum_{t=0}^{N} \frac{C_t}{(1+i)^t} \qquad \text{Eq. 2 – PVLCC}$$

Where:

Ct = the sum of all relevant costs occurring in year t,

N = length of the study period, years, and

i = the nominal discount rate.

The main PVLCC components are shown in Equation 3:

$$PVLCC\ = IC + PV\ (OM\&R + R + F - S) \qquad \text{Eq. 3 – PVLCC}$$

Where:

IC: Investment costs

PV: Present value obtained through the nominal discount rate (i);

OM&R = Operating, maintenance and repair costs;

R = Replacement costs;

F = Fuel (energy, water) costs;

S = Residual value (resale, scrap, salvage).

The nominal discount rate (i), considering an inflation rate (I) can be calculated as shown in Equation 4.

$$i = (1 + r)(1 + I) - 1 \qquad \text{Eq. 4 – Nominal discount rate}$$

Where:

r = real discount rate,

i = nominal discount rate and

I = general price inflation.

Life cycle perspective though the application of LCC allows the comparison of different scenarios extending the period analysis beyond the initial investments and can unveil the trade-offs necessary to justify the economic feasibility of the solutions. The Discounted Payback Period (ASTM E1121 2012) can also support the decision-making process, aggregating to the financial benefit to cost analysis

(ASTM E0964 2010), the time period necessary to recover the investments.

Additionally, to value of LCC, the following cost components must be considered to obtain the Whole Life Cost (WLC): external costs, income and non-construction costs. Depending on the effects, externalities can be negative or positive. The WLC (BSI ISO 15686-5 2008) calculation must consider the costs, as shown in Figure 5.

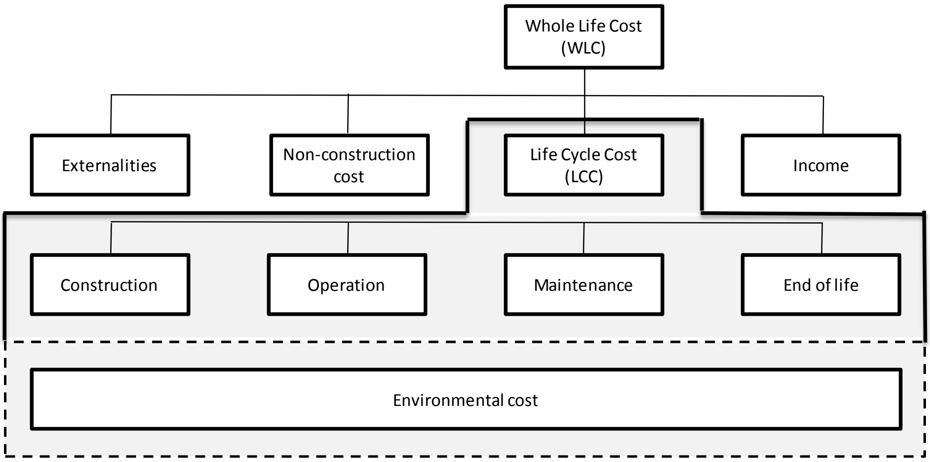


Figure 5 - WLC and LCC elements (BSI ISO 15686-5 2008)

The Present Value of WLC, named PVWLC, can be calculated through Equation 5, considering the following components:

- LCC (e.g. costs for construction, operation, maintenance, renovation);
- Externalities (e.g. additional travel time of road users, additional environmental pollution);
- Income (e.g. income from sales of constructed assets, tolls);
- Non-construction costs (e.g. site costs, interests).

$$PVWLC(t,i,WC) = \sum_{t=0}^{N} \frac{WC_t}{(1+i)^t} = \sum_{t=0}^{N} \frac{(EC+NCC-INC+C)_t}{(1+i)^t} \qquad (5)$$

Where:

Ct = the sum of all relevant costs occurring in year t;

EC = the sum of all relevant external costs occurring in year t;

NCC = the sum of all relevant non-construction costs occurring in year t;

INC = the sum of all relevant incomes occurring in year t;

N = length of the study period in years, and

i = the nominal discount rate.

4. Case Studies Overview

4.1. Case Study I - Constructed Asset – Logistics Centre

The Logistics Centre adopted is a logistic and service centre specialized in the food industry located in Spain. It provides services to other companies in the sector: renting spaces equipped with proper refrigeration chambers if required, offices, 24/7 security services, parking lots, waste separation and treatment and others.

Among the units in Figure 6 is emphasized the administration building, the warehouses 1, 2 and 3, the fish processing unit, the waste treatment and pressure units, and the parking lots of the Logistics Centre with overall consumption of about 650 MWh/year.

Figure 6 - Plan of the Logistics Centre with highlighted units in the scope of this case study.

This case study, modelled in TRNSYS 18, aimed to provide a more in-depth analysis into the energy and power consumption patterns of the main units of the Logistics Centre and highlight some recommendations for improvement by reducing the costs associated with the electric energy consumed from the grid.

The granularity of the Logistics Centre dataset (annual energy and power consumption in an hourly base profile), and its individualization by each of the main eleven units, allowed to envisage the effectiveness of combine multiple loads into a single load, to improve the solar fraction for the different simulated PV sizing and the optimization, via GenOpt, of a grid connected PV system.

4.2. Case Study II - Building – Integration of renewable energy and thermal energy storage in residential buildings.

A Hypothetical Building Model was configured, using the TRNSYS 18 (module Type 56), with 7 floors with 2,520m^2 divided into 42 units (6 units per floor, 2 x 40m^2, 4 x 70m^2). This model calculates the lightning and equipment electrical demand and the cooling demand necessary to maintain the level of comfort in the apartments (air nodes). The weather input data from Rio de Janeiro, were used for the simulations, however initial simulations with hourly data from two other cities in different locations in Brazil were used to detect the effects of the location in the building cooling demand and to verify the accuracy and reliability of the model. The temperature in the air nodes (apartments) were adjusted to 25 to 27 [^{o}C].

To attend the cooling demand an Air-Cooled Chiller System and a Thermal Energy Storage (TES) were also configured. The Chiller/TES set and its connection to the Hypothetical Building model is shown in Figure 7 ,and its electrical demand calculated and summarized with the lightning and equipment electrical demands, represented in Figure 8.

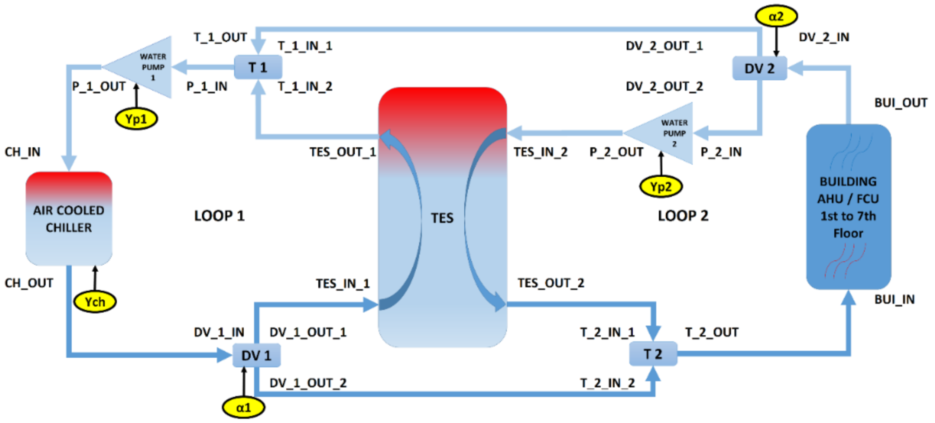


Figure 7 - Air-Cooled Chiller, TES and Building Air Handling Units (AHU)

The electrical demand of the building (lightning, equipment and cooling) was configured to be provided by a grid-connected PV system. Base on this configuration different scenarios were tested, aiming to reach the lower life cycle cost, via GenOpt optimization algorithm, varying the operating modes of the Chiller/TES set, according to the four ASHRAE operating modes, and the PV dimensions.

Figure 8 illustrate the integration of the TRNSYS Models and the GenOpt Optimization Algorithm, which the main modules are briefly explained below.

The module Type 15-2 reads the weather data file, obtained from the Energy Plus Weather Database, and feed both, the Type 190d (GRID-connected PV System Model) and the Type 56b (Hypothetical Building Model).

The module Type 9c reads the Building Model information. This information includes the cooling electrical demand, necessary to attend the building cooling demand and is calculated by the Model

Chiller/TES (see Figure 7). The lightning and equipment electrical demand is obtained directly from the Type 56b. The lightning and equipment hourly schedule of the apartments was configured according to standards and determine the respective electrical. Also, the persons occupation load schedule was configured, that influences the cooling demand.

The module Type 14h supplies hourly information of the variable tariffs, that contains the energy and power prices supplied by the GRID. The module Type 24 integrates the energy generates by the PV System and feeds this information to the Equation modules that are responsible to calculate the GRID supplementary energy, necessary to supply the whole building electrical demand. The module Type 583, the GenOpt Optimization Algorithm, has access to all the variables and can run the different configurations to obtain the minimum objective function value (e.g., the LCC).

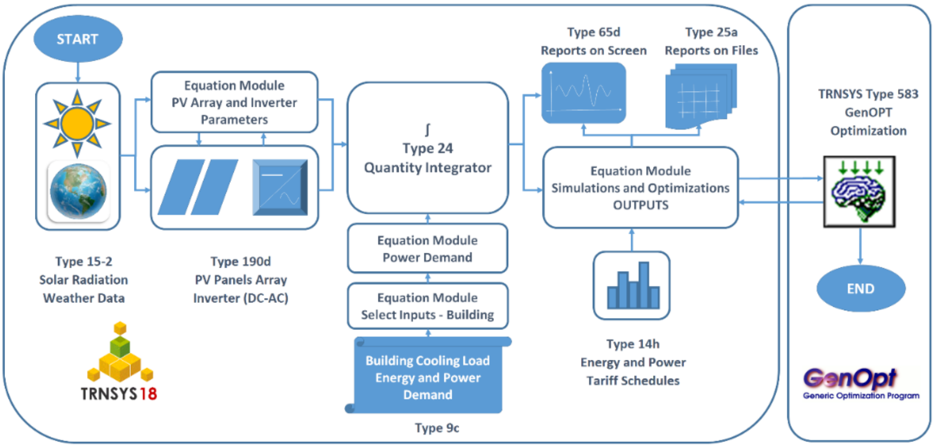


Figure 8 - TRNSYS model for Energy Efficiency simulations and optimization

II – Literature Review

This review focus on LCC Assessment (LCCA) and the adoption of this methodology for the economic pillar evaluation of the Sustainability Life Cycle in the Solar Energy sector. Research showed the effectiveness of this methodology as the main component for assessing sustainability in the economic domain, and the relationship with the primary methods of environmental and social areas.

The energy industry has been responsible for a significant number of publications, and the use of LCCA for different scale solar energy solutions as vehicles, houses, buildings, highways, rural properties and power plants indicates the usefulness of this methodology. In the large-scale solar energy solutions, for Solar Photo Voltaic (SPV) and Concentrated Solar Power (CSP), the use of LCCA can upraise the advantages for choosing or integrating both solutions. Also, clarifying the feasibility of their critical ancillary solutions, named Electrical Energy Storages (EES) and the Thermal Energy Storages (TES).

In minor scale solar energy solutions where the crescent technological evolution of SPV Cells has resulted in higher energy efficiency rates, the use of the LCCA can demonstrate the sensitive reduction on the Levelled Cost of Energy (LCOE), reflecting on the feasibility of solutions as the Zero Energy Buildings (ZEB).

These facts allied to the crescent number of studies and publications shows that LCCA is a promising field of studies and a powerful tool to achieve a most complete and reliable Life Cycle Sustainability Assessment of solar energy technologies and also the solar energy implementation projects, mainly in the design phase.

1. Introduction

A timeline of main Sustainable Development events published by Heather Creech (Creech 2012) from The International Institute for Sustainable Development (IISD), shows an overview of the main events related to the Sustainable Development from 1962 until now:

- 1962 - Silent Spring (Carson 1962)
- 1972 - The Limits to Growth: A Report to the Club of Rome (Meadows et al. 1972);
- 1987 - Our Common Future (Brundtland's Report): A Report of the World Commission on Environment and Development (WCED) (Brundtland et al. 1987);
- 1992 - Earth Summit: UN Conference on Environment and Development (UNCED) in Rio de Janeiro, that reaches agreements on the action plan Agenda 21, the Rio Declaration, and the non-binding Forest Principles.
- 1996 - The formal adoption of ISO 14001 - Environmental Management, as the voluntary international standard for corporate environmental management.
- 1997 - The formal adoption of ISO 14040 - Environmental Management - Life Cycle Assessment - Principles and Framework.
- 1998 - The formal adoption of ISO 14041 - Environmental Management - Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis.

- 1999 - Launch of the Dow Jones Sustainability Indexes, a tool that guides investors looking for profitable companies that follow sustainable development principles.
- 2008 - The formal adoption of BS ISO 15686-5:2008 - Buildings & Constructed Assets - Service life planning – Part 5: LCC (BSI ISO 15686-5 2008).
- 2012 - Rio +20 - Fifty years after Silent Spring, 40 years after Stockholm and 20 years after the Earth Summit, the global community reconvenes to secure agreement on “greening” world economies through a range of smart measures for clean energy, decent jobs and more sustainable and fair use of resources.

These publications, conferences, working groups, and countless initiatives are evidence of the growing concern about sustainability and its three pillars, according to the Brundtland’s Report (Brundtland et al. 1987), the environmental, social and economic dimensions.

The SETAC publications give us an idea of the first steps that resulted in the concept of Life Cycle Thinking. Because of the above mentioned UNCED (Rio 1992), the governments, international organisations and the private sector were called in Agenda 21 (Rio 1992) to develop criteria and methodologies for the assessment of environmental impacts and resource requirements throughout the full life cycle of products and processes. The last purpose at that time was assisting individuals and households to make environmentally sound purchasing decisions. It occurred in parallel with the first steps in the developments of LCA - Life Cycle Assessment (SETAC 2009).

Further on, the UNEP stated that was necessary to go beyond the traditional focus on production sites and manufacturing processes so that the environmental, social, and economic impact of a product over its entire lifecycle, including the consumption and end of use phase, would be considered entirely (SETAC 2009).

Despite the environmental and social aspects, the economic issues must be considered to keep the balance of the sustainability analysis. The literature review shows that LCC seems to fulfil these needs. It is a compilation and assessment of all costs related to a product, over its entire life cycle, from production to use, maintenance and disposal. The U.S. military in the 1960's first developed and utilised LCC to assess the costs of high living goods such as tanks and tractors (SETAC 2009).

Previous works related to LCC showed that the environmental and social issues were not the primary concerns. Along the years, LCC usefulness growing fulfilled the gap between the economic pillar in harmony with the environmental and social pillars for the LCSA. This fact is mainly due to the possibility to adapt, with some improvements, the LCC methodology to the life cycle thinking concept.

An overview and analysis of an amount of 7,910 published papers related to LCC since 1966, extracted from the Scopus Elsevier Database show the growing use of this methodology in the industry, infrastructure, construction, building sectors and so on. The publications of the British Standards Institute in 2008 with the BS ISO 15686-5:2008 Buildings and constructed assets - Service-life planning

- Part 5: Life-cycle costing (BSI ISO 15686-5 2008), compensated the lack of standardisation.

The principal objectives of this part of the ISO 15686 were stated as clear and practical. They enable the application of LCC to improve the decision making at important stages of projects. Moreover, to set out the guiding principles, instructions, definitions for different forms of LCC and reporting are stated in the ISO 15686.

Also, the Society of Environmental Toxicology and Chemistry (SETAC) has published in 2011 a Code of Practice for Environmental LCC (eLCC), which provides a framework for evaluating decisions with consistent, but flexible systems boundaries as a component of product sustainability assessments (Swarr et al. 2011). The code of practice was grounded in a framework for life cycle sustainability assessment (LCSA) of products. Swar et al. (Swarr et al. 2011), propose the conceptual equation that uses distinct analyses for each of the three pillars of sustainability: environment (LCA), economy (LCC), and social equity (sLCA), showed at Equation 1.

$$LCSA = LCA + LCC + sLCA$$ Eq. 1 - (Swarr et al. 2011)

The timeline at the beginning of this topic shows the crescent concern with sustainable development that reflects the growing demand and usefulness of a reliable Sustainability Assessment of projects, products and services. It results, for example, in the creation of technical committees like the CEN/TC 350 (European Committee for Standardization) in 2005, responsible for the production of standards that provides a system for the sustainability assessment of buildings using a life cycle approach (CEN 2005).

This literature review aims to prove that the LCC methodology is reliable and deserves international sustainable community attention as a bottom line not only for the Sustainability Assessment but the Life Cycle Sustainability Assessment in the Solar Energy sector. Also, is our goal to prove that the Solar Energy sector, that deals with one of the most important renewable energy resources, has been a close relationship with LCC for many years and this integration is fundamental to improve the sustainable development of this sector.

A brief analysis of the reviewed papers

In the literature review, at the final refinement, the 502 documents close related to LCC and Solar Energy were analysed in more detail, and 258 documents are listed in the Tables A1 to A5 in the Appendix. The analysis showed in the same Table can lead us to some conclusions about the evolution of the LCC concept, its relationship to the Solar Energy sector and the sustainability aspects.

The literature review shows that the Solar Energy issues are closely related to LCC as support for traditional and new technologies in the sector and involves concepts about cost-benefit analysis, design, simulation, optimisation, efficiency, life cycle analysis and so on. After that, but not far, it is possible to identify the feasibility studies of hybrid energy systems including wind power generation, as activities that make use of LCC to tune the share of each renewable energy resource that comprises a hybrid system, and to justify their investments.

Studies about the intrinsic characteristics of LCC, showed its evolution to an economic methodology, frequently related to environmental concerns as impact analysis of constructed assets, carbon emission, cost-benefit analysis and cost efficiency.

An overview shows that institutions with most publications are from USA (180). India (45), Canada (25), United Kingdom (25), China (22), South Korea (18), Turkey (17), Australia (14), Egypt (12), Germany (12), Malaysia (12), France (11) are the next countries, in number of publication. Bangladesh (10), Italy (10), South Africa (10). Nigeria (7), Spain (7), Iran (6), Japan (6) and Austria, Denmark, Finland and New Zealand (each one with five publications) come next. Using the data from Scopus Elsevier database (ADdress field) is possible to plot through the GPS Visualizer (A. Schneider 2002) the countries of affiliation of the authors and the percentage of publications about the 502 selected publications about LCC and Solar Energy, as shown in Figure 9.

Figure 9 - Articles related to LCC and solar energy extracted from Scopus Elsevier database (% per country)

The literature review (see Table A1) also shows conceptual studies about LCC published during the 1960's and 1970's decade, related to the use of this methodology by the decision makers when analysing different technical solutions. Despite the few numbers of publications, issues related to solar energy efficiency, mathematical modelling and optimisation, more specifically for water and air heating and water pumping proposes were the most common.

Papers discussing conceptual issues about LCC during the 1980's (see Table A2), gave particular attention to the economic aspects of the application of solar energy in buildings maintenance, retrofits, upgrading and their designs. Here are included studies related to the development of PV solar cells and solar collectors emphasising the solar radiation characteristics and expanding their application field beyond the space-related projects.

Next, during 1990's decade (see Table A3), there was an increment of papers about solar power generation, using of LCC to justify their choice compared to traditional power sources. Also, cost-effectiveness and performance studies of solutions become more common. Computer simulations are in evidence as a design support tool.

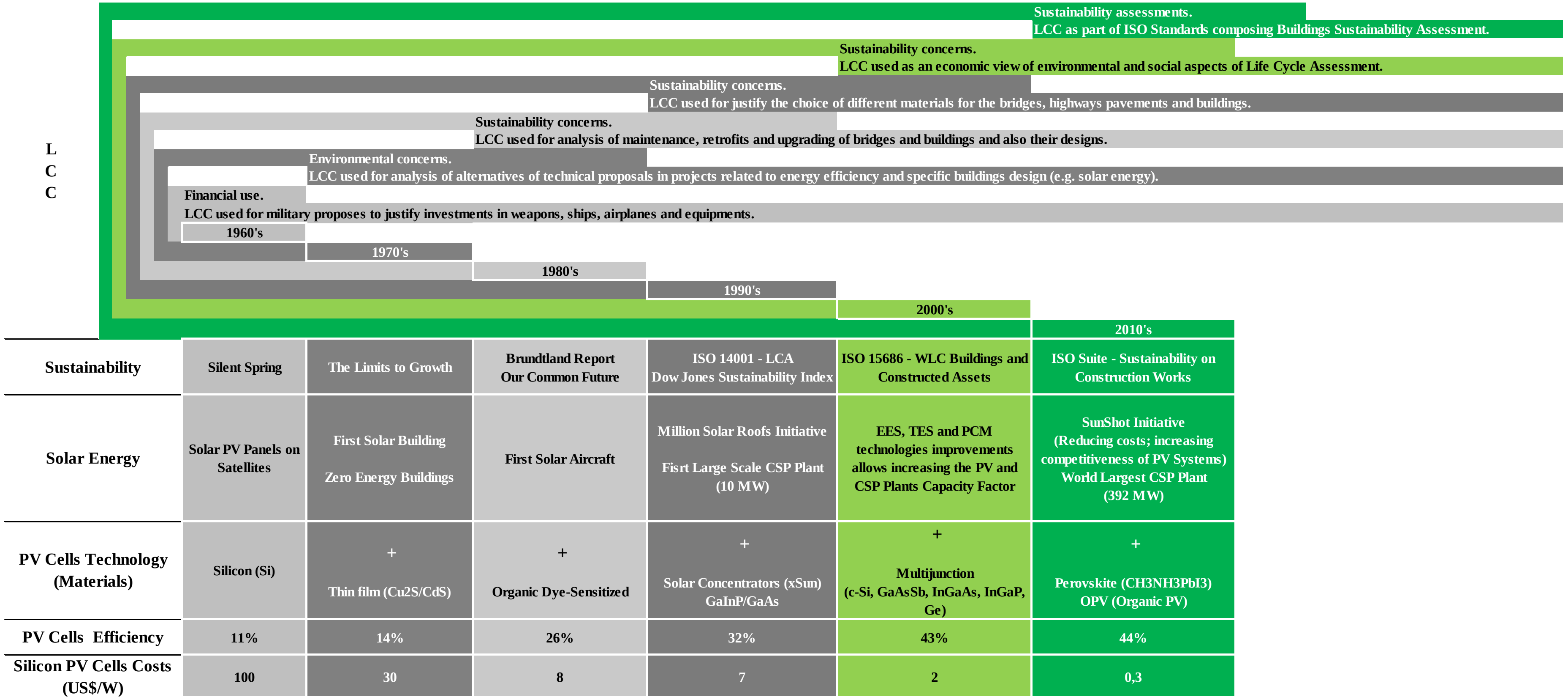
Succeeding, papers following the same topics than in the nineties were still in evidence during the 2000's decade (see Table A4). The use of hybrid systems mainly comprised of solar and wind energy are discussed and also energy conservation systems. The comparisons between PV and CSP and the evolution of their related electrical and thermal energy storage solutions are in evidence. At Table 1 there is a comparison of the main CSP technologies, published by the International Energy Agency (IEA 2010).

Table 1 – Main CSP technologies, adapted from (IEA 2010)

Technology	Annual Energy Efficiency	Land Occupancy	Water Cooling (L/MWh)	Solar Fuels	Energy Storage	Outlook for Improvements
Parabolic troughs	15%	Large	3000 or dry	Yes	Yes	Limited
Linear Fresnel receivers	8 – 10%	Medium	3000 or dry	Yes	Yes	Significant
Towers (central receivers)	15 – 35%	Medium	2000 or dry	Yes	Lmtd	Very Significant
Parabolic dishes	25 – 30%	Small	None	Lmtd	Lmtd	Via mass production

In recent years (the 2010's), the relation between LCC and LCA and the application of LCC for the economic aspects of environmental processes is reflected in some of the analysed publications. There are publications of literature review and papers about energy efficiency concerning to carbon emission analysis. Net Zero Energy Buildings (NZEB), Nearly Zero Energy Buildings (nZEB) and hybrid systems comprised of renewable energy resources, mainly solar and wind energy, are also in evidence (see Table A5).

After 2000, there was an increment of the number of papers and authors in LCC and LCA field. A summary about the PV technologies evolution at Figure 10, aligned with relevant milestones of sustainability, the solar energy sector in the last decades and the main improvements in the LCC methodology according to the reviewed papers, illustrates the close relationship of these knowledge areas.



	1960's	1970's	1980's	1990's	2000's	2010's
Sustainability	Silent Spring	The Limits to Growth	Brundtland Report Our Common Future	ISO 14001 - LCA Dow Jones Sustainability Index	ISO 15686 - WLC Buildings and Constructed Assets	ISO Suite - Sustainability on Construction Works
Solar Energy	Solar PV Panels on Satellites	First Solar Building Zero Energy Buildings	First Solar Aircraft	Million Solar Roofs Initiative Fisrt Large Scale CSP Plant (10 MW)	EES, TES and PCM technologies improvements allows increasing the PV and CSP Plants Capacity Factor	SunShot Initiative (Reducing costs; increasing competitiveness of PV Systems) World Largest CSP Plant (392 MW)
PV Cells Technology (Materials)	Silicon (Si)	+ Thin film (Cu2S/CdS)	+ Organic Dye-Sensitized	+ Solar Concentrators (xSun) GaInP/GaAs	+ Multijunction (c-Si, GaAsSb, InGaAs, InGaP, Ge)	+ Perovskite (CH3NH3PbI3) OPV (Organic PV)
PV Cells Efficiency	11%	14%	26%	32%	43%	44%
Silicon PV Cells Costs (US$/W)	100	30	8	7	2	0,3

Figure 10 – Timeline of LCC, Sustainability and Solar Energy Milestones

2. Methodology and Definitions

2.1. Methodology

For the literature review, the Scopus Elsevier Database was the primary source for retrieving articles and books. The refinement of LCC definitions came mainly from the International Standards Organization (ISO), British Standards Institute (BSI) and the publications of the Society of Environmental Toxicology and Chemistry (SETAC).

Our focus was to identify evidence of the close relationship between LCC and Solar Energy and to achieve this goal we conducted searches in both issues separately and further on in conjunction. For the Solar Energy issue, after verifying the vast amount of information contained in the Scopus Database (almost 94 thousand documents), authors decided to begin with a broader approach and further on with successive refinements. For the LCC (and WLC) issue we have tracked the same steps (initially almost 8 thousand documents). This approach is practical and has support on publications of bibliometric and bibliographic specialist authors as Rowley and Frances (Rowley and Frances S 2012).

We consider that was an appropriate method because, in the end, we retrieved about 500 documents close related to LCC and Solar Energy, published since 1966. In other words, this review covers a range of 50 years of LCC-Solar Energy published papers. At the Results topic and Tables A1 to A5 in the Appendix, these documents are analysed in more details to support and justify our main conclusions.

The use of Bibliometric Software VOSviewer (Nees Jan van Eck; Ludo Waltman 2015) that has smooth integration with the Scopus Elsevier Database was essential to guide our steps and assure that we were in the right way. It allowed us, for example, analyse 4 thousand keywords and 11 thousand terms from Titles and Abstracts at the same time and categorise them, based on their relevance or occurrence. The documents were downloaded from Scopus in a comma separated format to VOSviewer, to compose the clusters aiming to categorise the documents and identify the main issues discussed, its relatedness and the primary sources. The Results topic details the analysis of these searches. These were the steps:

1 – Search with keyword “Solar” and “Energy” in Title and Abstract fields, limited to English language and Subject Areas Engineering and Energy.

Retrieved 93,744 documents published since 1882.

2 – Search with keyword “Solar” and “Energy” in Source Title field, limited to the English language. Retrieved 26,883 documents published since 1957.

At this point, could be identified two central Journals, “Solar Energy” and “Solar Energy Materials and Solar Cells”, responsible for 62% of the publications retrieved on item 2.

3 – Search with exact source title “Solar Energy”, limited to the English language.

Retrieved 8,903 documents published since 1957.

4 – Search with exact source title “Solar Energy Materials and Solar Cells”, limited to the English language.

Retrieved 8,213 documents published since 1992.

At this point, the main issues related to Solar Energy were identified and categorised in clusters, showed at the Results topic.

5 – Search with keyword “Life Cycle Cost” or “Whole Life Cost” and their variances in Title and Abstract fields, limited to the English language. Retrieved 7,970 documents published since 1966.

6 – Search with the keyword (“Life Cycle Cost” or “Whole Life Cost”) and (”Solar” or ”Energy”) in Title and Abstract fields, limited to the English language. Retrieved 2,304 documents published since 1966.

7 – Search with the keyword (“Life Cycle Cost” or “Whole Life Cost”) and (”Energy”) in Title and Abstract fields, limited to the English language. Retrieved 2,183 documents published since 1970.

8 – Search with the keyword (“Life Cycle Cost” or “Whole Life Cost”) and (”Solar Energy”) in Title and Abstract fields, limited to the English language. Retrieved 189 documents published since 1975.

9 – Search with the keyword (“Life Cycle Cost” or “Whole Life Cost”) and (”Solar”) in Title and Abstract fields, limited to the English language. Retrieved 502 documents published since 1966.

At this point, the main issues related to LCC and Solar Energy were identified and categorised in clusters, showed at the Results topic and the Tables A1 to A5 in the Appendix.

10 - For the plotting of the Geolocation we have used the GPS Visualizer (Global Positioning System), an application supplied by Google Inc. For the extraction

of the country names and their number of occurrences and insertion in the GPS Visualizer to plot on the earth map, we have used the data extracted from Scopus Elsevier Database in RIS format and a Bibliometric Software, BibExcel (Persson, O., R. Danell 2009).

2.2. Definitions

Different levels of Life Cycle Costing (LCC)

Considering the three pillars of sustainability: economic, environmental and social, different kinds of sustainability assessments can be distinguished per the pillar(s) they deal with (Brundtland et al. 1987). In this way, Klopfer (Klöpffer 2003) defines Life Cycle Sustainability Assessment (LCSA) as the complete assessment integrating the three pillars. Investors often view the environmental considerations as obstacles to business development, particularly within the short term and this is where the concept of LCC seems to emerge.

Blanchard and Fabrycky (B S Blanchard and Fabrycky 1990) define LCC as an assessment of all costs associated with the life cycle of a product that is directly covered by any one or more of the actors in the product lifecycle (supplier, producer, user/consumer, EOL-actor).

In the same line, most recently, Hunkeler et al. (Hunkeler et al. 2003) point out that LCC is an essential link for connecting environmental concerns with core business strategies, as a view derived from discussions in international working groups relating to Life Cycle Management (LCM). They remind the fact of LCC to integrate economics and the environment aspects as part of the Kyoto Protocol and still include the implementation of initiatives as Design for Environment (DfE) and Integrated Product Policy (IPP) within companies and along supply chains.

Four levels of assessments can be distinguished in the literature: financial LCC (fLCC), environmental LCC (eLCC), full environmental LCC (feLCC) and social LCC (sLCC) (Finkbeiner et al. 2010). Table 2 presents the components from the simplest to a complete LCC. fLCC is part of eLCC, which in turn is part of feLCC which is finally part of sLCC.

Table 2 – Different levels of LCC according to their scope

	Level of LCC	Scope	Description
LCC	Conventional, Traditional or Financial LCC	Economy	One actor (supplier or consumer)
eLCC	Environmental LCC	Economy Environment	One or more actors (supplier, producer, user / consumer and those involved at the end-of-life)
feLCC	Full Environmental LCC	Economy Environment	One or more actors (extends eLCC with monetized, non-internalized environmental costs)
sLCC	Societal LCC	Economy Environment Society	One or more actors (costs are borne by anyone in society)

The LCC basic calculation formulas are presented in the publications of the American Society for Testing and Materials (ASTM E0917 2015a) and are summarised in the Equations 2, 3, 4 and 5. The Present Value of LCC, named PVLCC, can be calculated as follows:

$$PVLCC\ (t, i, C)\ =\ \sum_{t=0}^{N} \frac{C_t}{(1+i)^t} \qquad \text{Eq. 2 – PVLCC}$$

Where:

Ct = the sum of all relevant costs occurring in year t,

N = length of the study period, years, and

i = the nominal discount rate.

The main PVLCC components are shown in Equation 3:

$$PVLCC\ =\ IC + PV\ (OM\&R + R + F - S) \qquad \text{Eq. 3 – PVLCC}$$

Where:

IC: Investment costs

PV: Present value obtained through the nominal discount rate (i);

OM&R = Operating, maintenance and repair costs;

R = Replacement costs;

F = Fuel (energy, water) costs;

S = Residual value (resale, scrap, salvage).

The nominal discount rate (i), take into account the inflation rate (I) and can be calculated as shown in Equation 4.

$$i = (1 + r)(1 + I) - 1 \qquad \text{Eq. 4 – Nominal discount rate}$$

Where:

r = real discount rate,

i = nominal discount rate and

I = general price inflation.

Conventional Life Cycle Costing or Financial Life Cycle Costing (LCC or fLCC)

As mentioned by Ness et al. (Ness et al. 2007), the Conventional LCC assessments are only focused on private investments from one actor (a firm or consumer) and named financial LCC (fLCC). Rebitzer and Nakamura (Rebitzer and Nakamura 2008) explained that generally, only costs related to the actor matter, not considering the environmental costs or external end of life costs. Consequently, a fLCC does not always cover the complete life cycle. They still remind that a common practice is to discount the cash flows that occur within the period of the product lifecycle.

Norris at al. (Norris, Road, and Berwick 2001) showed that some financial items included in fLCC are for example investment costs, research and development (R&D) costs, and sales revenues (presented as negative costs). Although the focus usually lays on these private costs, sometimes user costs are included, for example, if companies are developing new products, they may take their customer's cost of ownership into account.

Environmental Life Cycle Costing (eLCC)

According to Swarr et al. (Swarr et al. 2011), the eLCC extends a traditional LCC because it assesses all costs associated with a product life cycle that is covered by one or more of the actors. These actors include suppliers, manufacturers, customers, end-users or EOL actors. While eLCC does not include external costs non-related to real monetary, it does look at the substantial external costs of social externalities or environmental impacts.

Rebtizer et al. (Rebitzer and Hunkeler 2003) gave detailed definitions of internal and external costs. They explained that the **internal costs** are those costs occurred in the life cycle of a product (a producer, transporter, consumer or another stakeholder directly involved in the product system value chain) is paying for the production, use or EOL expenses. In summary, these costs are the business expense. The *external costs* are mainly those costs that are accounted in monetary units and cover the financial costs from actors outside the product system value chain, for example, municipal waste recovery fees and indirect health costs.

As a proof of the improvement of the LCC method, Koepfler and Ciroth (Kloepffer and Ciroth 2011) explain that, in contrast to traditional LCC, the eLCC is fully compatible with LCA and allows assessing the costs of products from different points of view.

Full environmental LCC (feLCC)

Hoogmartens et al. (Hoogmartens et al. 2014) explain that the full environmental LCC (feLCC) is not a commonly accepted concept in the world of sustainability assessment tools, but it can be useful to show in an explicit way that eLCC is in no way an equivalent of eLCA. They argue that feLCC extends eLCC with monetised, non-internalized environmental costs that can be identified by an environmental assessment method such as eLCA. However, they agree that the transition to convert environmental impact figures to monetised measures is not always straightforward.

Social or Societal LCC (sLCC)

According to Hoogmartens et al. (Hoogmartens et al. 2014), the sLCC includes all costs accepted by anyone in the society, whether today or in the future, and associated with the life cycle of a product. Impacts such as public health and human well-being have to be quantified and translated into monetised measures, which is often a challenge in carrying out this type of assessment. The transfer payments like subsidies and taxes should be subtracted from the cost data as they have not net cost effect, as emphasised by Massaruto et al. and Rus (Massarutto, Carli, and Graffi 2011), (de Rus 2010).

Rabl (Rabl 1996) pointed out that sLCC applies different discounting ratings over the years emphasising that from a society perspective, there should be a preference for low discount rates. This idea is approved most recently by Rambaud and Torrecillas (Rambaud and Torrecillas 2005).

Between the four levels of LCC, the sLCC is a complete LCC and it presents similar information than the Whole Life Cost (WLC) which was defined by the BSI ISO 15686-5 Standard (BSI ISO 15686-5 2008).

Whole Life Costing (WLC) – Standard for LCC application

According to the BSI ISO 15686-5 (BSI ISO 15686-5 2008), additionally to LCC, the following cost components must be taken into account: external costs, income and non-construction costs. Depending on the effects, externalities can be negative or positive. The WLC calculation must consider the following costs, as shown in Figure 11:

- LCC (e.g. costs for construction, operation, maintenance, renovation);
- Externalities (e.g. additional travel time of road users, additional environmental pollution);
- Income (e.g. income from sales of constructed assets, tolls);
- Non-construction costs (e.g. site costs, interests).

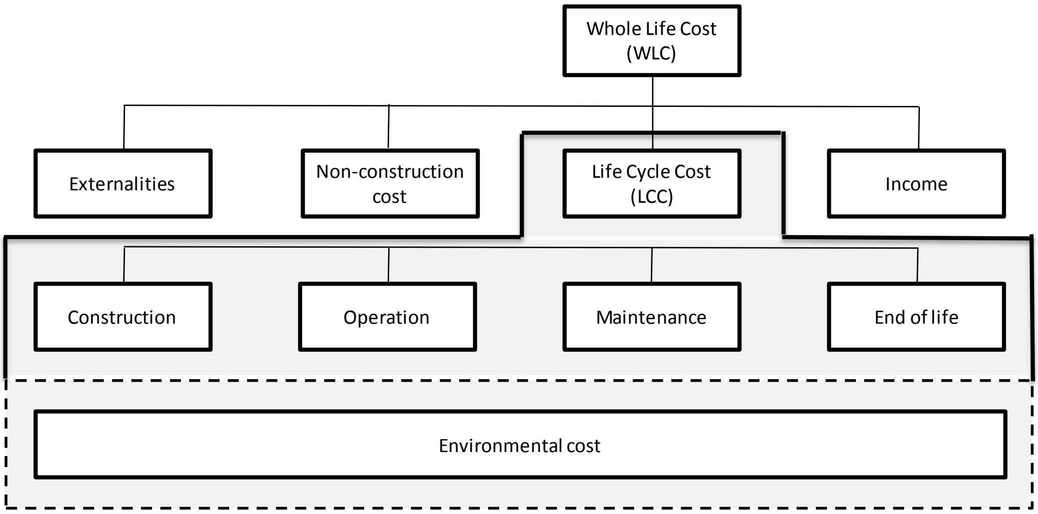


Figure 11 – WLC and LCC elements (BSI ISO 15686-5 2008)

The relationship between LCC, LCA and Sustainability assessment

Blanchard (Benjamin S. Blanchard 1979) reminded that LCC predates LCA, and both had distinct conceptual foundations and methodological approaches traced from its developmental roots in engineering systems. Authors argued that despite the recognised value of LCC for sustainability assessments, lacks integration between these methods (Norris, Road, and Berwick 2001), (Hunkeler et al. 2003), (Kloepffer 2008b).

Ortiz et al. (Ortiz, Castells, and Sonnemann 2009) defined LCA as a methodology that analyses the whole life cycle of a product or a system, based on the triple bottom line of sustainability, that concerns environmental, social and economic aspects. Joshi and College (Joshi and College 2000) completed that LCA represents a tool for systematically analysing the environmental performance of products or processes over their entire life, including raw material extraction, manufacturing, use, EOL disposal and EOL recycling. Hence, LCA is often considered a “cradle to grave” approach to the evaluation of environmental impacts.

Kloepfer (Kloepffer 2008a) explained that Environmental LCC (eLCC) summarises all costs associated with the life cycle of a product that is directly covered by one or more of the actors and follows a basis analogous to LCA. Both include the definition of a functional unit and similar system boundaries. The same author reminded that although an LCA should be available for the same product system, an LCC can also be performed as a standalone assessment.

Hauschild et al. (Hauschild, Dreyer, and Jørgensen 2008) and Karina et al. (Karina et al. 2011) pointed out the development of two LCA types, eLCA and sLCA, that has application separately or in combination to deal with different pillars of sustainability.

Swarr et al. (Swarr et al. 2011) summarised in the Code of Practice for Environmental LCC, the framework for life cycle sustainability assessment (LCSA) of products and established through the conceptual equation, LCSA = eLCA + LCC + sLCA, the relationship between these methodologies. The author considers the three pillars of sustainability, named environment (LCA), economy (LCC), and social equity (sLCA). As defined above, is essential to remember that a complete LCC, the sLCC or WLC, should be considered.

The ISO 21929-1 (ISO 21929-1 2011) brings the LCC as one of the fourteen core indicators for assessing the sustainability in buildings, considering the costs aspects. The role played by LCC from a sustainability perspective and its close relationship with the Sustainability Assessment. LCC has a direct impact in the economic capital area of protection and an indirect effect on the economic prosperity.

Life Cycle Engineering (LCE)

Alting (Alting 1995) defined LCE as the relatedness of the life cycle thinking and the development of products and services, during the concept phases of the projects. Still, according to Alting, LCE is the design the product lifecycle through choices about product concept, structure, materials and processes, as shown in Table 3. The LCA is the tool that visualises the environmental and resource consequences of these choices, integrated with the LCC for the economic assessment.

Table 3 – Design strategies through the Life Cycle (Alting 1995)

	Phase	Strategy	Relevance
Life Cycle	**Pre-manufacture**	Use of recycled materials	Resource Depletion (RD), Environmental Burdens (EB)
		Use of less energy intensive materials	EB
		Environmental conscious component selection	EB, Supplier Performance
	Manufacture	Use high-throughput process	EB, Working Environment
		Use material saving processes	RD, EB
		Overhead reduction	EB
	Transportation & Distribution	Improved logistics	EB
		Low volume / weight	EB
		Use recycled material for packing	RD, EB
	Use	Low energy consumption	RD, EB
		Design for maintenance / long life	RD
	Disposal	Design for Disassembly (DfD)	RD
		Material quality preservation	RD, EB

LCC Tools

The most common tools for LCC calculation consists of worksheets used to gather the life cycle data all together in a single document, e.g. NIST, Simple WERF, Harvard and Stanford. These are some tools and solutions, but the demonstration of *how they work* is not the scope of this review:

- **NIST:** The National Institute of Standards and Technology (NIST) has published a manual titled “the LCC manual for the Federal Energy Management Program (FEMP)” also named NIST Handbook 135 (Akhlaghi 1987). Also had developed the software “*Building Life Cycle Cost (BLCC)*” which provides economic analysis of capital investments.
- **Simple WERF**: The Sustainable Infrastructure Management Program Learning Environment – Water Environment Research Foundation - SIMPLE WERF has developed the Life Cycle Cost Projection Tool - LCCP Tool (SIMPLE WERF 2010). This LCCP Tool is useful as a step by step guide for the management assessment practitioner who requires assistance in developing a life cycle cost projection and subsequent analysis.

- **HARVARD**: The Harvard Green Building Standards (Trimble 2011), published by The Harvard University assists project management by vetting or setting sustainable goals and objectives. The Harvard LCC Calculator Worksheet is intended to provide information related to the economic impact of energy conservation measures (ECM) over a 20-year time. Allows identifying the mains results are the net present value, the total cost of ownership, and the GHG savings based on the prices and GHG factors.
- **STANFORD:** Guidelines for LCC assessment for land and buildings (Stanford 2005), published by The Stanford University in the USA, that balances initial monetary investment with the long-term expense of owning and operating the building. They agree about basic LCCA assumptions that multiple building design options can meet programmatic needs and achieve acceptable performance and that these options have different initial costs, operating costs, maintenance costs, and possibly different life cycles.

3. Results

3.1. Bibliometric Analysis

In the first searches using the keys "LCC or WLC" (and its most common variants, Life Cycle Costs, Life Cycle Costing, Whole Life Costs, Whole Life Costing) a set of 7910 documents is revealed. A cluster analysis of these documents allows the refinement of the further searches.

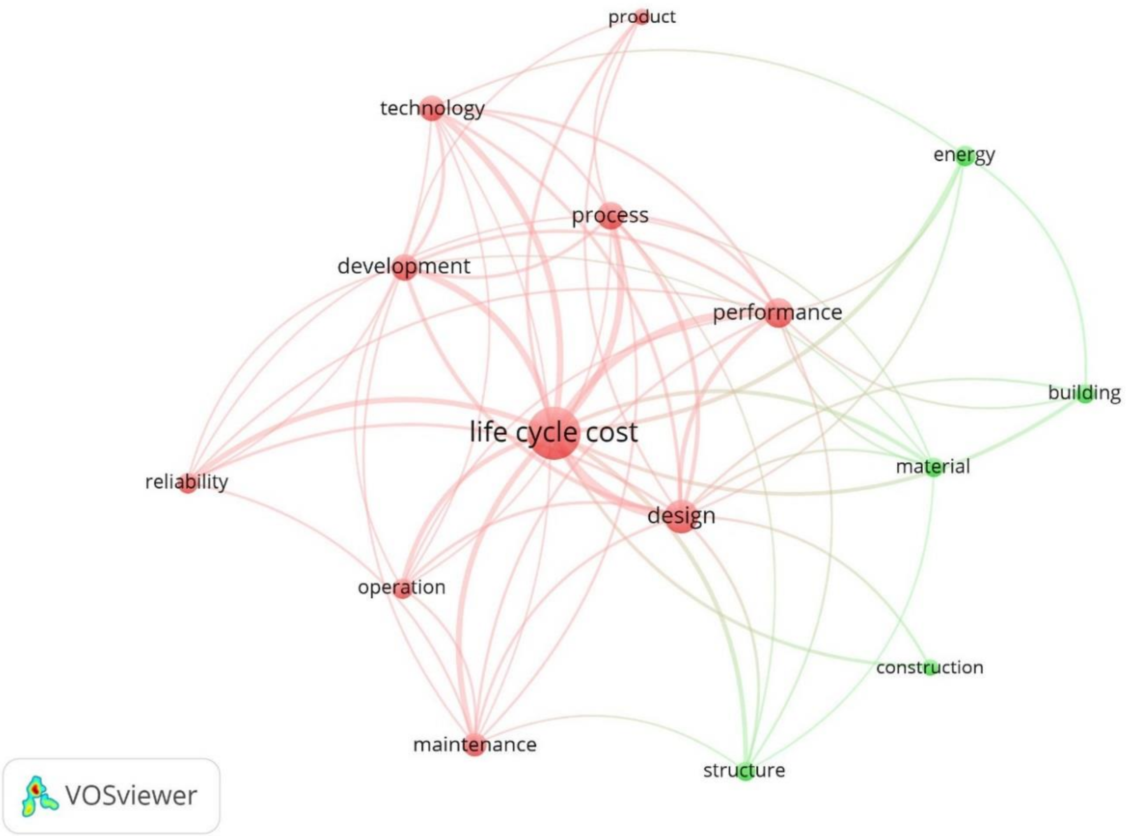


Figure 12 – LCC, WLC and most related issues

Figure 12 shows some initial results, in the first cluster, for example, we can find the main concerns related to LCC, named performance, design, maintenance, operation, reliability, development, process, technology and product. In the second cluster, the main applications or industry sectors can be inferred, named building, energy and material, followed by construction and structure, can help in the refinement of the searches. The high occurrence of "Energy" term, closely related to

LCC, and building, design, performance and technology, allows concluding the relationship between these two issues.

The next refinement step was the inclusion of "Energy" key in the search, related with a logical (.AND.) operator to the previous keys, "LCC" or "WLC". The results plotted in Figure 6 shows the main aspects of this issue, now limited to 2,183 documents, almost one-third of the initial set of 7,910 documents from the first search.

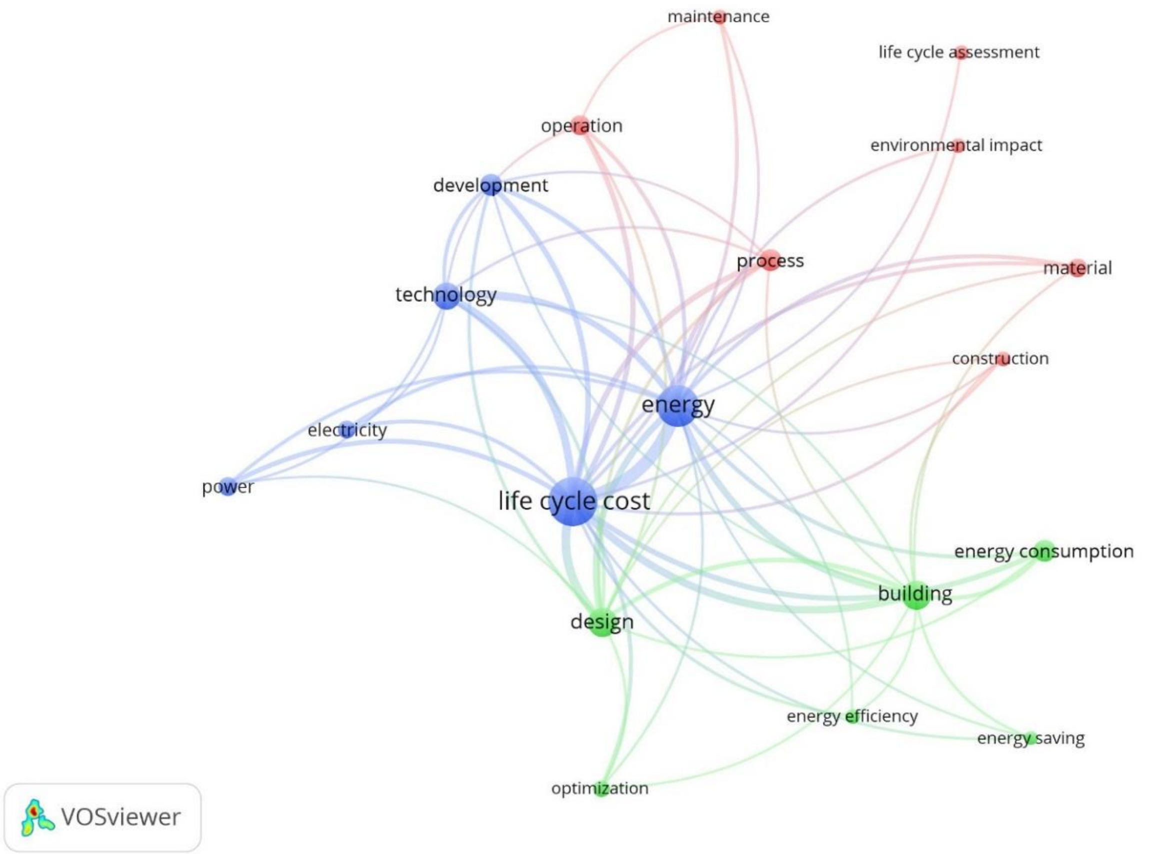


Figure 13 – LCC, WLC, Energy and most relates issues

Figure 13 sheds light on the issues energy consumption, energy saving and energy efficiency, closely related to building, design and optimisation. Also, the Life Cycle Assessment (LCA) and environmental impact aspects become more evident, closely related to material, construction, process, operation and maintenance. The operation and maintenance aspects, now represented in a separate cluster, confirms the common sense expressed in most documents about the relevance of these aspects in the LCC of buildings and constructed assets, even with the “Energy” filter applied in this search.

Before to go further with the literature review related to LCC and Solar Energy, the focus of this document, we conducted a search in the Scopus Elsevier Database using the keyword “Solar” and retrieved 92,706 documents published since 1882. The ancient publications, were done 135 years ago, by the Journal of the Franklin Institute discussing solar energy conservation (Chase 1882), (Siemens 1882) and further on the distribution of energy in the solar light spectrum (C. Fabry and Buisson 1922), evidencing the main concerns of the academic community at that time.

These searches also allowed us to verify that the periodical publications related to solar energy research started in 1957, sponsored by the Solar Energy Journal (Mathur and Khanna 1957; Furnas 1957), (Sihvonen, Majkowski, and Slater 1958; Tabor 1958), (Shaffer and Speyer 1959; Elliott 1959), (Kapur 1960; Löf 1960). The Proceedings of the Institute of Radio Engineers – IRE, since 1963 named Proceedings of IEEE also were responsible since that time for periodical publications in this area (Aarons, Barron, and Castelli 1958; Piddington 1958), (Biermann and Lüst 1959; D. K. Bailey 1959), (Daniel 1960; Wolf 1960).

The Solar Energy Materials and Solar Cells Journal started in 1992 the periodical publications of documents related to these issues and at the moment of this search it was responsible for 8,175 publications, against 8,863 from the Solar Energy Journal. Both are responsible for about 62% of the retrieved publications in English in this area, according to the Scopus Elsevier Database. Figure 14 shows the annual publications from 1957 to 2016.

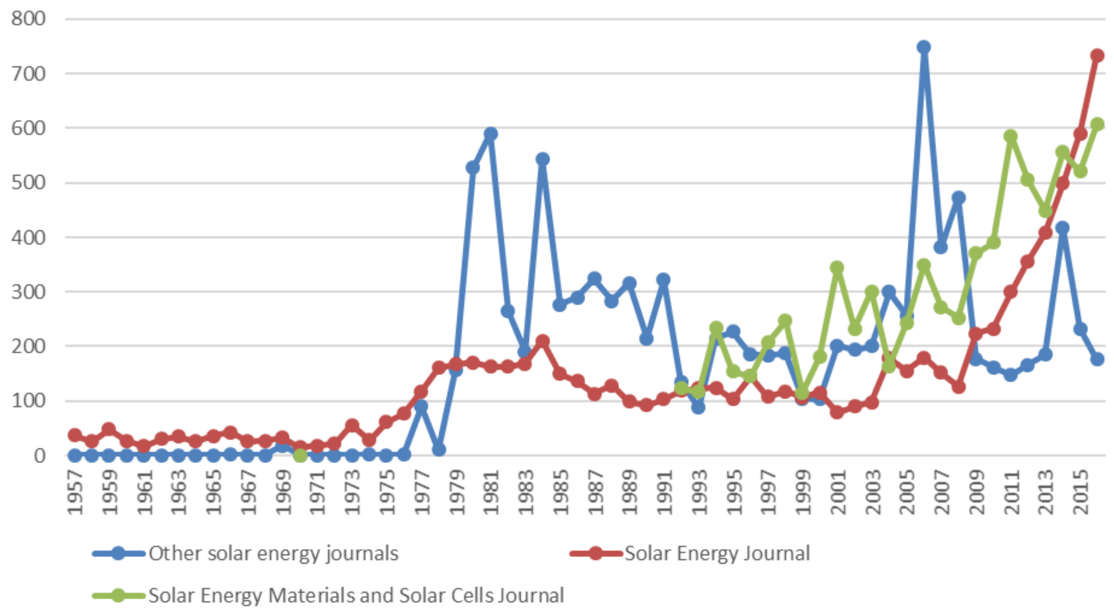


Figure 14 – Publications about the issue Solar Energy (1957 – 2016)

To get a whole picture of the solar energy scenario we did a refinement in these initial searches. Considering the 26,521 retrieved documents about solar energy issues, published since 1957, extracted in the Scopus Elsevier Database, we submitted them to the cluster analysis.

Considering the "Index Keywords" field, we have identified 64,773 distinct terms and setting a minimum occurrence of 450 times (if it occurs in the same documents, the weight is fractionalized, to avoid distortions), 57 terms are the most relevant and shown in Figure 15.

The overlay visualisations allow to better identify the most relevant terms, according to the legend, where the blues colour the keywords with fewer citations by other documents, and the red colour means those with most citations. For example, "mathematical model" has 1,691 occurrences or 1.21 average normalised citations (red) by the documents meaning that this keyword is more relevant, and "solar radiation" has 4,100 occurrences, but it has 0.21 average normalised citations (blue). It means that despite the common use as a keyword, it has fewer citations considering the Titles and Abstracts fields of the documents. In other words, the term "mathematical model" and the other terms in red are a cluster that is more relevant for this set of documents that "solar energy" and the other terms in blue.

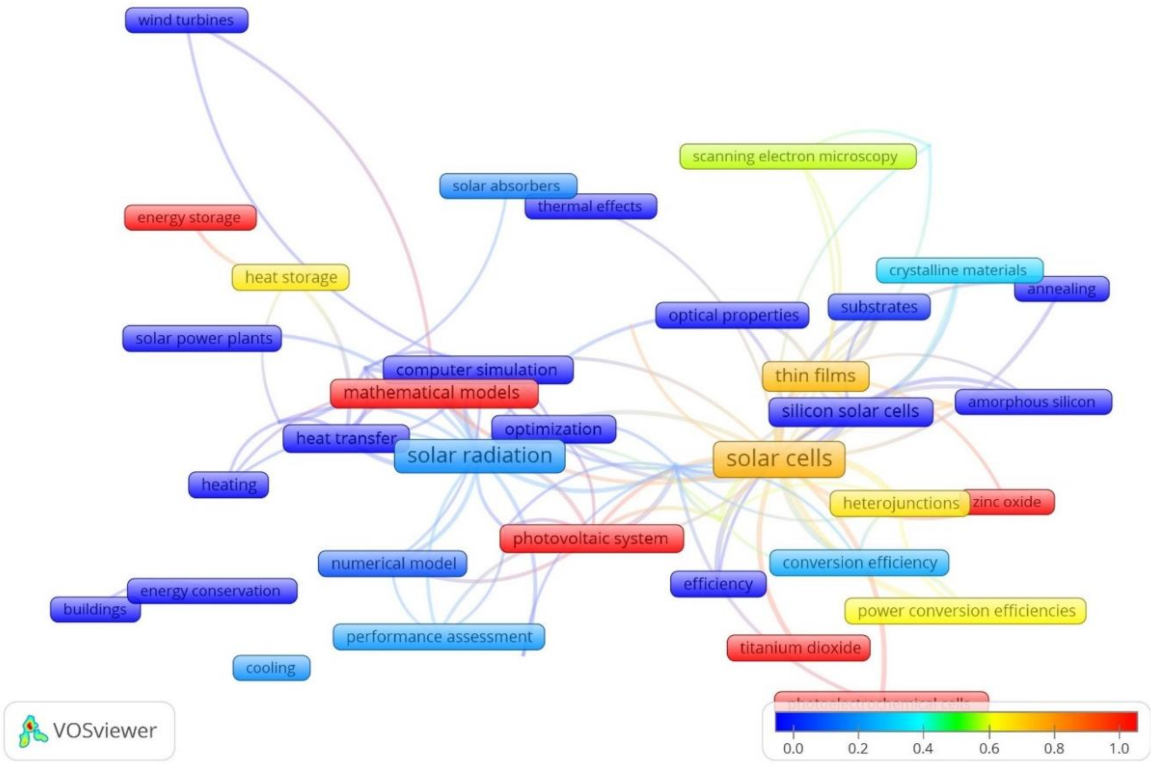


Figure 15 – Solar Energy and the most related issues (1957 – 2017)

Orbiting around the most occurred terms, we can find some relevant issues in this area. Around “solar cells”, there are “titanium dioxide”, “zinc oxide”, “thin films”, “power conversion efficiencies”, and so on. Around “solar radiation”, there are “mathematical models”, “photovoltaic system”, “energy storage”, “heat storage”, “performance assessment”, and so on.

Following the searches related to LCC and Solar Energy, the next refinement step was the inclusion of “Solar” key in the search, related with a logical (.AND.) operator to the previous keys, “LCC” or “WLC”. The term “Solar Energy” were experimented but it narrowed the results (189 documents) and excluded some important documents, because of another term used by the authors, as “Solar Power”, “Solar Systems”, Solar PV” and “Solar Thermal”.

The results plotted in the Figure 16 shows in two clusters the main aspects and its relatedness, now limited to 502 documents, 23% from the previous set of 2,183 documents, and about 6% of the initial set of 7,910 documents related to LCC, WLC and Energy.

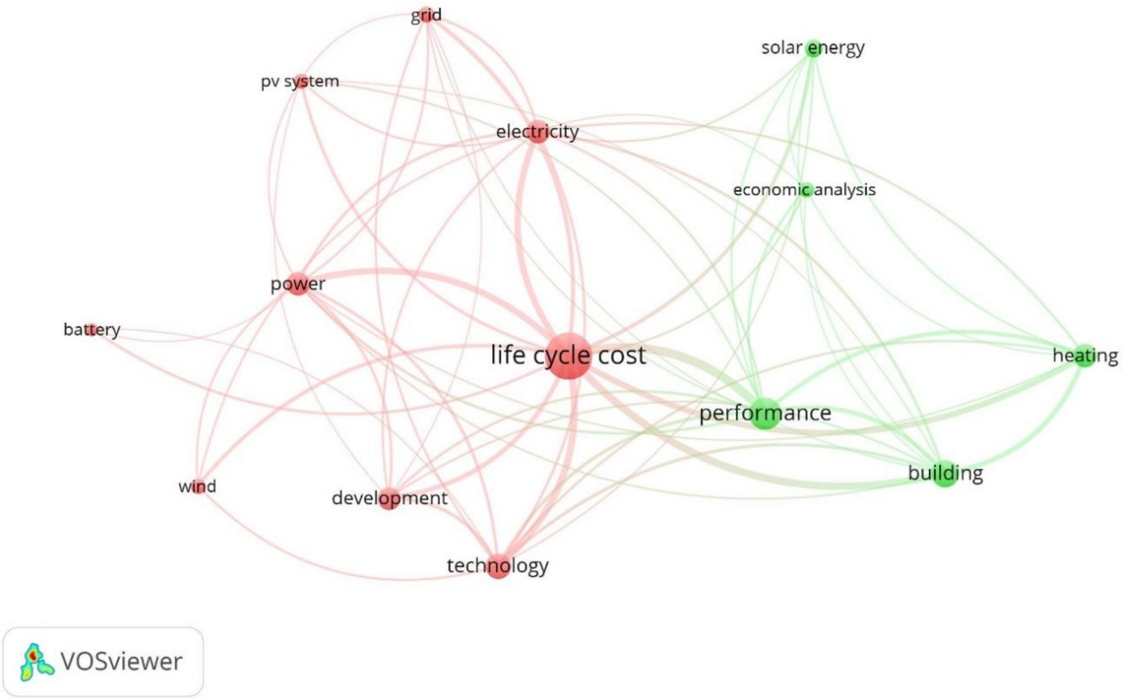


Figure 16 – LCC, WLC, Solar Energy and most relates issues

Figure 8 shows the close relationship between solar energy and electricity, performance, economic analysis, technology and heating, still closely associated with building in a cluster. Despite the close relation to LCC, electricity and technology, the other cluster arises the connection with the grid, PV system, power, battery and development. The relation with the wind in this set of documents, calls attention to hybrid systems, which the further bibliographic analysis will confirm, also the articles showed in Tables A1 to A5 in the Appendix.

3.2. Bibliographic Analysis

The bibliometric analysis of retrieved documents, based on clusters and later refinements, showed the use of LCC in energy projects, specifically solar energy projects and solutions. Based on the final set of 502 documents, of which 258 are detailed in the Tables A1 to A5 in a decade categorisation, we show in the next topics the primary concerns of the scientific community concerning the solar energy issue, categorised according to the most relevant keywords and terms.

Solar Radiation

The most ancient studies about solar radiation retrieved in the literature review date from 1922 when Fabry and Buisson (C. Fabry and Buisson 1922) discussed the curve of energy distribution in the ultraviolet part of the solar spectrum. Although this subject is still under investigation.

Sihvonen et al. (Sihvonen, Majkowski, and Slater 1958) presented a solar radiation instrument, called a Spectre heliometer, that continuously records and integrates the sun's radiant power in five selected wavelength intervals, and also incorporates a pyrheliometer to measure overall solar radiation. Landsberg (Landsberg 1961) studied the characteristics of solar radiation on the earth surface and recorded annual solar radiation intensity on the horizontal surface from over 300 locations. The author incorporated these data into a world map. Besides the uncertainty of values over the oceans, he concluded that the highest intensity centres around 22° latitude north and south on most continents, it means close to the Cancer and Capricorn tropic lines which are at +23.5º and -23.5º latitude respectively.

The accurate measurement and forecast of solar radiation energy potential has been a concern of the academic community, as it represents a critical input for the design of solar energy solutions. Shu et al. (Shu et al. 2006) detailed in their studies some factors that influences the appropriate conversion of solar energy radiation using PV cells. They have obtained for their location an annual solar energy potential of 1,237.63 (kWh/m^2).

Most recently, Charabi et al. (Charabi, Gastli, and Al-Yahyai 2016) pointed out that during the last decade significant progress has been made to develop multiple solar irradiance databases (Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI)), using a satellite of different resolution and sophisticated models. The authors assess the performance of High-resolution solar irradiance derived with dynamical downscaling Numerical Weather Prediction model with, GIS topographical solar radiation model, satellite data and ground measurements, for the production of what they call "bankable solar radiation data sets". They argue that such precision is necessary for the financial viability of solar energy project. According to them, accurate estimation of solar energy resources in a country is essential for proper siting, sizing and LCC analysis of solar energy systems.

Solar Collectors

The solar collectors are one of the most common issues in the literature review, commonly associated with LCC analysis, mainly because of the contribution of these components to the whole cost and their influence on the energy efficiency of the solar energy solutions. Kalougirou (Soteris Kalogirou 2007) studied the patents of solar collectors and categorised them into two types, mainly the non-concentrating or stationary and the concentrating. The author also studies the tracking mechanism that allows the collector to follow the apparent movement of the sun with precise accuracy.

Kumar et al. (V. Kumar, Shrivastava, and Untawale 2015) analysed the Fresnel lens as a promising alternative of reflectors in Concentrated Solar Power (CSP), due to its potential to overcome techno-commercial constraints of conventional reflector based CSP. They point out that the significant challenges associated with such plants are the high costs of the reflector or mirror (50% of total cost of installation) and a high LCC. Some years before, Hernández-Moro and Matínez-Duart (Hernández-Moro and Martínez-Duart 2012) developed a mathematical closed-form expression for the evaluation, in the period 2010-2050, of the Levelled Cost of Energy (LCOE) based on the LCC of Concentrating Solar Power (CSP) electricity, briefly described in Equation 5. They have considered the evaluation of the available solar resource, based on the analysis of the International Energy Agency (IEA) for predicted values for the cumulative installed energy capacity and a Degradation Factor (DR) to calculate the energy produced annually "t" years after the installation, described in Equation 6.

$$LCOE\ (t, i, LCC) = \frac{PVLCC_N}{\sum_{t=1}^{N} \frac{E_t}{(1+i)^t}}$$ Eq. 5 – LCOE (US$/MWh)

Where:

$PVLCC_N$: Present value of LCC (US$) (see Eq. 2 and Eq.3);

E: Energy produced annually by the plant (MWh);

i: Nominal discount rate (%) (see Eq. 4);

N: Estimated life time of the systems (year);

t: Year.

$$E_t = S\ .TF\ \eta(1 - \mathrm{DR})^t$$ Eq. 6 – Energy produced annually (MWh)

Where:

S: Available Solar Resource or Direct Normal Irradiance (DNI);

TF: Tracking Factor;

η: Performance Factor (amount of utilised solar resource per produced energy);

DR: Degradation Factor.

Corona et al. (Corona et al. 2016) investigated the use of Full Environmental LCC (feLCC) methodology to evaluate the economic performance of a 50 MW parabolic trough Concentrated Solar Power (CSP) plant operating in hybrid mode with different natural gas inputs (between 0% and 30%). They concluded that solar-only operation remains as the best option due to hybridisation with natural gas be economically unattractive.

Solar Energy Conversion - Thermal and Photovoltaic

The literature review showed that the solar energy conversion had important initial improvements due to the research and implementations in satellites, spacecraft and space stations related projects. The use of those technologies came further on to the terrestrial solar energy projects and another renewable energy source in a variety of hybrid systems.

In the field of thermal energy conversion, Talbert et al. (Talbert et al. 1975) compared the results of a systems analysis and economic study of a photochemical solar energy system with a conventional hot-water solar energy system, considering conversion efficiency, energy storage capacity, and LCC as the primary basis of comparison. Dochat and Vitale (Dochat and Vitale 1986) proposed in their publication, a Free Piston Stirling Engine (FPSE) connected directly with a linear alternator and heated via solar energy is attractive as a solar thermal electric power conversion system. They emphasised its high efficiency, long life, high reliability, low maintenance and an initial and LCC adequate to become a commercial product.

Chiasson and Yavuzturk (Chiasson and Yavuzturk 2003) assessed the viability of hybrid geothermal heat pump (GHP) systems with solar thermal collectors and used the LCC analysis to delineate the economic viability, considering the drilling costs.

The hybrid systems are the object of many publications. In their work, Kumar and Tivari (S. Kumar and Tiwari 2009) presented the LCC analysis of single slope hybrid photovoltaic thermal (HPVT) active solar stills. They compared the payback and the energy payback time (EPBT) of both, passive and active systems. Romero Rodriguez et al. (Romero Rodríguez et al. 2016) presented the optimisation aspects at the analyses of economic feasibility and reduction of a building's energy consumption and emissions using integrated hybrid solar thermal / PV / micro-combined heat and power (CHP) systems.

Sathe and Dhole (Sathe and Dhoble 2017) most recently researched on PVT technologies historical and developments and pointed out the advantages of thermal integrated with PV systems for thermal energy generation and heat extraction aiming to keep its temperature at satisfactory level so that it can work efficiently.

Besides the integration between thermal and PV technologies is possible to verify the growing concern of researchers in the solar cells and the evolution of the technologies.

Studies conducted by Wolf (Wolf 1961) presented in a review, the state-of-the-art in SPV energy conversion as applied to space vehicle power supplies. He discussed the characteristics of silicon solar cell and gave a survey of the progress made in the application of other semiconductor materials to SPV energy conversion. Biss and Hsu (Biss and Hsu 1983) described a space station application of silicon and gallium arsenide solar cells and the mechanical design of a low concentration ratio solar array.

Preble and Trible (Preble and Tribble 1996) performed the LCC and technical analysis while studying the feasibility of a Small Solar Probe designed for a space mission to Jupiter, considering the use of a solar array rather than a radioisotope thermoelectric generator as the power source. Mansour (Mansour 2003) also used the LCC approach in his work for enhancing the efficiency of solar cells and extending their performance life. He investigates the influence of a thin luminescent layer on the efficiency of a solar cell and the effect of three different modules of luminescent solar concentrators on the performance of the cell.

The PV solutions are studied by Azzopardi et al. (Azzopardi, Mutale, and Kirschen 2008), that developed a methodology based on LCC and sensitivity analysis to determine cost boundaries for new PV solar cell technologies. They aimed to establish cost boundaries for future PV technologies efficiently be competitive within the PV market from that time. Also, concluded that a price reduction factor greater than five would be competitive for future solar cell lifetimes of less than 4-5 years. Espinosa et al. (Espinosa et al. 2013) studied the organic PV for mobile applications. Evaluate the roll-to-roll processed indium and silver free polymer solar cells through analysis of LCC and layer quality using inline optical and functional inspection tools.

The patents are also an important issue that can influence future research. Louwen et al. (Louwen et al. 2016), in their recent work, traced the cost roadmap for silicon heterojunction solar (SHJ) cells. They show that research and development of

SHJ solar cells have seen a marked increase since the recent expiry of core patents. Using LCC, they analyse the current cost breakdown of these SHJ designs, compared to conventional diffused junction monocrystalline silicon modules.

Solar Thermal and Electrical Energy Storage

The Thermal Energy Storages (TES) that captures and stores heat or cold and the Electrical Energy Storages (EES), that stores electrical energy in solid state batteries or flow batteries, are the most common energy storage systems retrieved in the literature review as solutions for the intermittency, seasonal characteristics and the optimisations of renewable energy resources. We have also found studies about the Flywheel Storages and the Hydrogen Storages.

In their studies, Jones and Lior (Jones and Lior 1979) developed an insulation design procedure for solar heating system piping and water-filled thermal storage tanks. They show the sensitivity of solar systems to cost, in a present-value LCC analysis. Some years before, Talbert et al. (Talbert et al. 1975) have already studied the energy storage capacity issue using LCC as a base of comparison. In the same line, Davidson and Walker (Davidson and Walker 1992) performed the sensitivity analysis for the storage volume of water in a solar water heater.

Alkhamis and Sherif (Alkhamis and Sherif 1997) studied the feasibility of a solar-powered heating/cooling system for an aquatic centre using Thermal Energy Storage tanks for the collector and domestic use. They perform an economic analysis based on the LCC method. Isherwood et al. (Isherwood et al. 2000) present an analytical optimisation of a remote power system for a hypothetical Alaskan village, along with the possibility of using advanced energy storage technologies to take full advantage of the intermittent renewable sources availability.

Important results related to TES and the use of PCM were achieved by (Gil et al. 2010) and (Medrano et al. 2010) in their complementary studies about high temperature TES for power generation. Rezaei et al. (Rezaei et al. 2013) also studied the performance and economic aspects PCM with different melting temperatures in heating systems and point out that their analysis help choosing the best PCM regarding the lowest LCC for the usage in TES.

The literature review evidenced the use of Energy Storages as a feasible solution to optimize the capacity factor of solar power plants, as shown by Starke et al. (Starke et al. 2018). The annual based capacity factor (8,760 hours) of a power plant, can be calculated trough the Equation 7.

$$CF = \frac{E_{net}}{8760 \, . \, W_{nameplate}} \qquad \text{Eq. 7 – Capacity Factor}$$

Where:

E_{net}: Annual net energy delivered by the power plant (MWh)

$W_{nameplate}$: Nominal capacity of the power plant (MW)

Concerning the Electrical Energy Storage systems, Okou et al. (Okou et al. 2011) performed the design and analysis of an electromechanical energy storage system to enhance rural electrification in sub-Saharan Africa. Using an LCC analysis they found significant cost savings by integrating a Flywheel Storage system into a Solar Home System when compared with lead-acid batteries.

Raj and Ghosh (Raj and Ghosh 2012) studied the Hydrogen Storages. They have conducted an economic analysis of standalone PV-diesel system versus PV-H2 system and point out that with steeply rising fossil fuel prices and developments in H2 technology, globally more regions will be cost-effective for PV-H2 systems. In the same line, Iverson et al. (Iverson et al. 2013) verified the optimal design of hybrid renewable energy systems (HRES) using hydrogen storage technology for data centre applications. They demonstrated a significant reduction in the LCC of the system when controllable power demand is considered, especially in regions where the wind and solar resources are relatively low.

Zakeri and Syri (Zakeri and Syri 2015) examined the existing literature in the analysis of LCC of electricity storage systems, providing an updated database for the cost elements (capital costs, operational and maintenance costs, and replacement costs). They analysed LCC and levelled cost of electricity delivered by electrical energy storage, employing Monte Carlo method to consider uncertainties. The optimisation of battery energy storage systems (BESS) can be verified in the work of Marchi et al. (Marchi, Pasetti, and Zanoni 2017), which emphasised the relevance of BESS to overcome the issue of intermittent production of energy based on renewable energy resources. They proposed an LCC model, which take into account all the most relevant cost components during the entire operation of the system.

Solar Energy Conversion Efficiency

The efforts of the scientific community for increasing the efficiency of Solar Energy Systems are evidence of how promising this field could be for future research. The mathematical models, the simulation tools like TRNSYS, MATLAB, and multi-objective analysis are in evidence in the optimisation studies. The research for new materials for solar cells, phase change material for thermal energy storages, presented above can be included in these efforts.

Groumpos and Papageorgiou (Groumpos and Papageorgiou 1987) presented an optimal sizing method for stand-alone PV power systems, mathematically formulating the total LCC, developing an algorithm for the solar array and battery capacity. Davanagere et al. (Davanagere, Sherif, and Goswami 1999) studied the feasibility of a solar desiccant air-conditioning system with a transient simulation for thermal and economic LCC analysis.

Belfkira et al. (Belfkira, Barakat, and Nichita 2008) performed the sizing optimisation of a hybrid wind/PV system with battery storage. They develop the mathematical model of the principal elements of the system showing the main sizing variables and uses a deterministic algorithm to minimise the LCC of the system while guaranteeing the satisfaction of the load demand. Valan Arasu et al. (Valan Arasu, Sornakumar, and Arasu 2008) study a solar Parabolic Trough Collector (PTC) hot water generation system and points out that MATLAB computer simulation program is appropriate to estimate the life cycle savings of other renewable energy systems performs.

Elzahzky et al. (Elzahzby et al. 2014) modelled the effect of inter-cooling on the performance and economics of solar energy assisted hybrid air conditioning system and validate the results with the experimental data. They also investigate the LCC. Badea et al. (Badea et al. 2014) performed the LCC analysis of passive house prototype and created a mathematical model, including its technical design variations. Every house was differentiated by the type of renewable solution used or by the insulation thickness and compared with a standard house with traditional HVAC systems. Koo et al. (Choongwan Koo et al. 2015) developed an integrated multi-objective optimisation (iMOO) model for establishing a low-carbon scenario to achieve carbon emissions reduction target for the residential building sector.

Rad et al. (Rad, Fung, and Leong 2013) analysed the feasibility of combined solar thermal and ground source heat pump systems in a cold climate and examined with TRNSYS simulation tool the viability of hybrid ground source heat pump (GSHP) systems that use solar thermal collectors as the supplemental component in heating dominated buildings. Also, using TRNSYS, Romero Rodríguez et al. (Romero Rodríguez et al. 2016) analysed the economic feasibility and reduction of a building's energy consumption and emissions when integrating hybrid solar thermal/ PV / micro-combined heat and power (CHP) systems.

Net/Nearly Zero Energy Buildings

Both, the Net Zero Energy Buildings (NZEB), as defined by the National Renewable Energy Laboratory (NREL) (Pless and Torcellini 2010) and the Nearly Zero Energy Buildings (nZEB), from the European Commission (Hermelink et al. 2013), are typical applications of renewable energy resources, mainly Solar Energy. In the European context, public policies are establishing goals and schedule for implementation such as the Energy Performance of Buildings Directive (EPBD) (EU 2010), and are evidence of the solar energy solutions importance. The hybrid systems comprised of the wind and solar energy produced on-site and off-site, are frequently found in the literature, associated with LCC.

Leckner and Zmewreanu (Leckner and Zmeureanu 2011) presented the Net Zero Energy House (NZEH), an energy efficient house that uses available solar technologies to generate at least as much primary energy as the house uses over the course of the year. They use computer simulation results show that it is technically feasible to reach the goal of NZEH in the cold climate regions and perform also the LCC analysis. Marzsal and Heiselberg (Marszal and Heiselberg 2011) also conducted an LCC analysis of a multi-storey residential Net Zero Energy Building (NZEB), considering three alternatives; PVT collectors and solar-sourced heat pump, PV with ground-source heat pump and PV with district heating grid. They discuss the NZEB cost-effectiveness and feasibility, mainly based on energy saving measures.

Kapsalaki et al. (Kapsalaki, Leal, and Santamouris 2012) developed a methodology and an associated LCC calculation platform in order to identify the economic efficient design solutions for residential Net Zero Energy Building (NZEB) in three climates scenarios, considering the influence of the local climate, the endogenous energy resources and the local economic conditions. Hamdy et al. (Hamdy, Hasan, and Siren 2013) discussed cost-optimal solutions for nearly-zero-energy buildings (nZEB). They compared combinations of energy-saving measures

(ESM) and energy supply systems including renewable energy sources (RES) and emphasised that an optimal implementation of ESM and RES depends significantly on the heating/cooling system and the escalation rate of the energy price.

Most recently, Paiho et al. (Paiho, Pulakka, and Knuuti 2017) analysed the LCC of different heat pump based nZEB concepts for the new detached house and a new apartment building, including different heat pumps without and with solar systems. They concluded that the LCC was the smallest with the ground source heat pumps (GSHP) followed by the air-to-water heat pumps.

4. Conclusions

There is a crescent interest for the LCC practices, as shown by the papers analysed across these almost 50 years contributed to the improvement of these practices and resulted in a methodology for the LCC. At the Definitions topic, we showed the evolution and the different levels of LCC, from the purely financial aspects, including further on the environmental and recently the social issues.

The international standards about LCC, mainly those related to the construction and energy industries are evidence of the consolidation of the methodology, which has a harmonious relationship with LCA. This harmony is enough to consider the LCC Assessment the primary methodology used to represent the economic domain to compose the triple bottom line for the sustainability assessment (LCSA) with the LCA acting on the environmental and social domains. Despite this crescent evolution of the life cycle methodology verified on the papers and standards, the use of LCC seems to be more common as an isolate financial support tool.

The close relationship between LCC and Renewable Energy Resources solutions are typical in the literature review, because of the first one has used as a justification for the implementation investments of the last one. For the Solar Energy solutions, this integration is more evident, mainly because of the preference for this resource in the renewable energy solutions, against the others renewable resources. The existing gap between the amount of solar energy available on the earth surface and the efficiency of conversion and storage of this energy to attend the demands contributes to this preference.

We showed that LCOE, an important decision-making prerequisite present at the evaluation of different renewable energy solutions, depends intrinsically on the LCC calculation.

The ancillary solutions related to PV and CSP, as EES and TES contribute to the improvement of the Capacity Factor of those solutions but represent an increase in their initial investment costs. However if their implementation costs are considered in a life cycle perspective, their feasibility can be demonstrated.

LCC methodology as a standalone practice in the Solar Energy sector is not recommended because of the need for integration of this practice in the complete sustainability assessment of the projects. This lack of integration seems to be the most common mistake when trying to apply the LCC methodology in this field.

The Solar Energy sector is up-and-coming, although, to assure the sustainability of the solutions, either in the research of new technologies or the design and implementation phases of the existing solutions, we do recommend attention to the Life Cycle Sustainability Assessment, in the terms discussed in this paper.

III – Case Study I – Logistics Centre

Often the selected solar systems for buildings are analysed from an energetic and economic point of view rather than from detailed feasibility analysis and a life cycle perspective. The energy supplied by the photovoltaic (PV) panels connected with the grid brings more flexibility for energy management; however, the energy surplus is an essential factor to be considered. Our objective is to evaluate with pre-design modelling and simulation the electrical demand of a Logistics Centre and determine the adequate system configurations, considering the Life Cycle Costing (LCC). We established a baseline and three alternative scenarios for optimization. Combining the use of TRNSYS 18 - Simulation Studio and its optimization library component, GenOpt - Generic Optimization Program, we simulated different options of grid energy contracts, considering the variable tariffs and the integration with PV. Based on the LCC the GenOpt performed the Single-Objective Optimization (SOO) process, also considering the Payback Period (PBP) of investments. This approach allowed envisaging possible configurations reducing up to a quarter of annual grid energy consumption and around 21% the LCC in a timeframe of 20 years. The PBP of investments is below six years. These results serve as input for the design and operation set up.

3. Introduction

Logistics Centres are common in cities where the balance between the transportation costs (from the producers to the consumers), storage costs, and other factors, make viable their implementation. The energy operation consumption for the preservation of perishable foods, waste disposal, air conditioning, space, and parking lightning, represent a relevant share of their total costs. These factors motivated the authors to expand this study, that could be limited to a report addressed to the Logistics Centre owners, into an article aiming to allow other researchers to access these energy efficiency results and, if convenient, reproduce their applicability to these so present buildings in cities all over the world.

The energetic and economic aspects of a logistic centre energy demand represent a variety of configurations that were used as a base to this analysis.

The Logistics Centre adopted is a logistic and service centre specialized in the food industry located in Spain. It provides services to other companies in the sector: renting spaces equipped with proper refrigeration chambers if required, offices, 24/7 security services, parking lots, waste separation and treatment among others. In Figure 17 the plan of the whole site with the distribution of the available spaces is shown. The specific units of interest for this study are highlighted and specified in the legend.

Figure 17 - Plan of the Logistics Centre with highlighted units in the scope of this study.

This study aims to provide a more in-depth analysis into the energy and power consumption patterns of the main units of the Logistics Centre and highlight some recommendations for improvement by reducing the costs associated with the electric energy consumed from the grid.

Among the units in *Figure 17* is emphasized the administration building, the warehouses 1, 2 and 3, the fish processing unit, the waste treatment and pressure units, and the parking lots of the Logistics Centre with overall consumption of about 650 MWh/year.

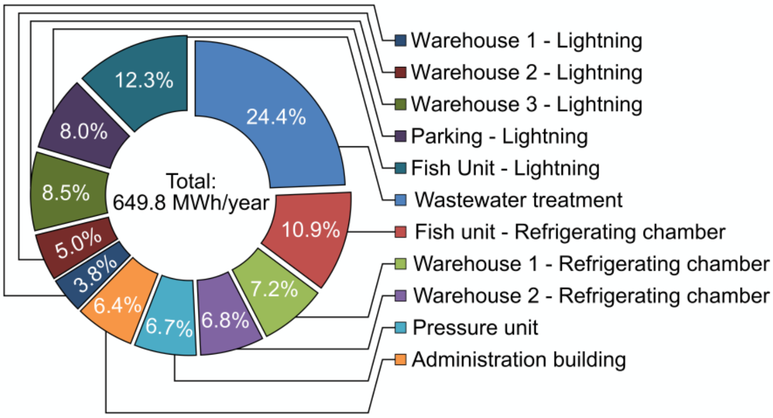


Figure 18 - Annual energy consumption shares of the studied units.

The shares of annual electric energy consumption required for the operation of each unit are provided above in *Figure 18*, where 24.4% corresponds to the wastewater treatment, 24.9% - to cooling in refrigeration chambers, 37.7% - to the lightning of the spaces.

The granularity of the Logistics Centre dataset, mainly its individualization by each of the main eleven units, allowed to envisage the effectiveness of combine multiple loads into a single load, in order to improve the solar fraction for the different simulated PV sizing.

The average solar irradiation in the location of the Logistics Centre is about 1.77 MWh/m^2/year, which represents a potential of 188 kWh/m^2/year of electrical energy using typical PV panels/inverters, considering the efficiency of 11%.

Figure 19a illustrates the summary of the hourly energy consumption (red), that allows verifying an average energy consumption of 162 MWh, during the most intense period of solar radiation, between 10 h and 16 h (yellow), representing 25% of the 650 MWh consumed the whole year. Preliminary calculations, considering no energy surplus (green), show that PV panels distributed over an area of 911 m^2 could supply this amount of energy with a solar fraction around 27%, however, the detailed modelling, simulation, and optimization, reveal that these numbers can be refined.

A hypothetical situation is shown in Figure 19b, aiming to clarify the need of the detailed calculations, where PV panels distributed over an area of 3,340 m^2 would be able to supply the total annual energy consumption of the studied Logistics Centre (650 MWh). This amount of energy would represent a solar fraction of around 41%, meaning that the 59% of energy surplus, produced between 9 h and 17 h (green) must have its allocation carefully planned.

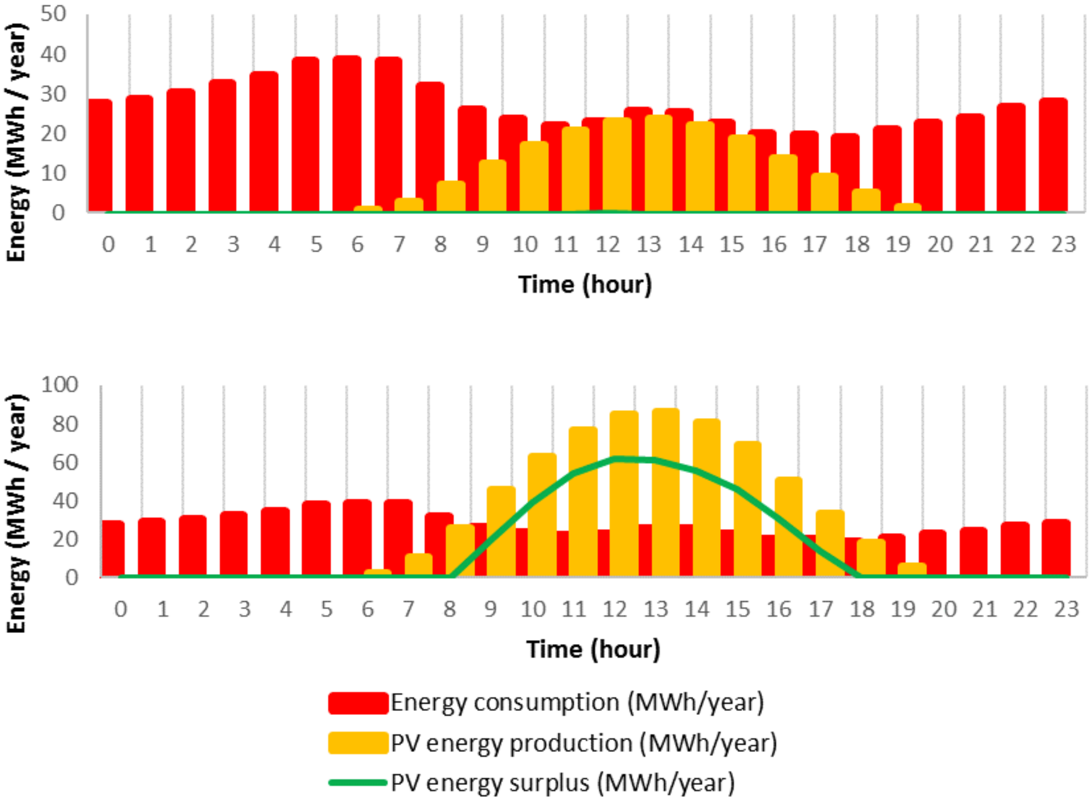


Figure 19 - (a) PV supplying partial energy demand, no surplus; (b) PV supplying partial energy demand, with a surplus.

During the optimizations, we approach the issue of surplus energy that can occur with the installation of panels beside a specific number. Beyond this point, the PV economic feasibility depends on the alternatives to deal with surplus energy.

As the literature review unveils, there are some possible uses for the PV surplus energy, that can be analysed from an economic point of view (not mentioning the environmental and social aspects), however, can bring quite different business autonomy effects, for example:

- sell to the grid (usually a trade-off of energy credits);
- storage in batteries
  - to shift the solar energy peaks;

  - to expand the business (e.g., implement electric vehicles charging stations)

The main objectives of this study are the evaluation of the current energy consumption patterns of the Logistics Centre facility, identification of possible improvements by the reduction of the overall expenses and, as a result, drawing of a series of recommendations to be potentially implemented. We adopted a life cycle perspective for the power and energy analysis (detailing the modes of contracting - separate units or together) and the insertion of PV in the last scenario aiming to improve the autonomy concerning the grid supplier.

After a brief literature review, the next sections include a description of the studied facility, specification of the current situation, the methodology and the case studies in section 2; next, the quantitative results in section 3 and their discussion in section 4; and finally, some conclusions and recommendations in section 5.

1.1 Literature Review on energy efficiency measures in logistic centres

Accessing the Elsevier Scopus scientific database (Elsevier 2019), some keywords related to this study were selected and searched at the documents fields titles, abstracts, and keywords, in order to retrieve the most relevant publications. The Boolean combination of keywords ("Energy Efficiency" OR "Energy Consumption" OR "Renewable Energy" OR "Solar Energy" AND "Logistics Center" OR "Logistics Centre" OR "Parking") resulted in a set of 544 documents published since 1975 to the present. These documents were categorized in 5 clusters, using the VOSviewer Bibliometric Software (Van Eck and Waltman 2009), according to the occurrence frequency of 1,289 author keywords, to envisage the main concerns and findings of the academic community related to this sector. Figure 20 shows these main concerns in the most recent publications.

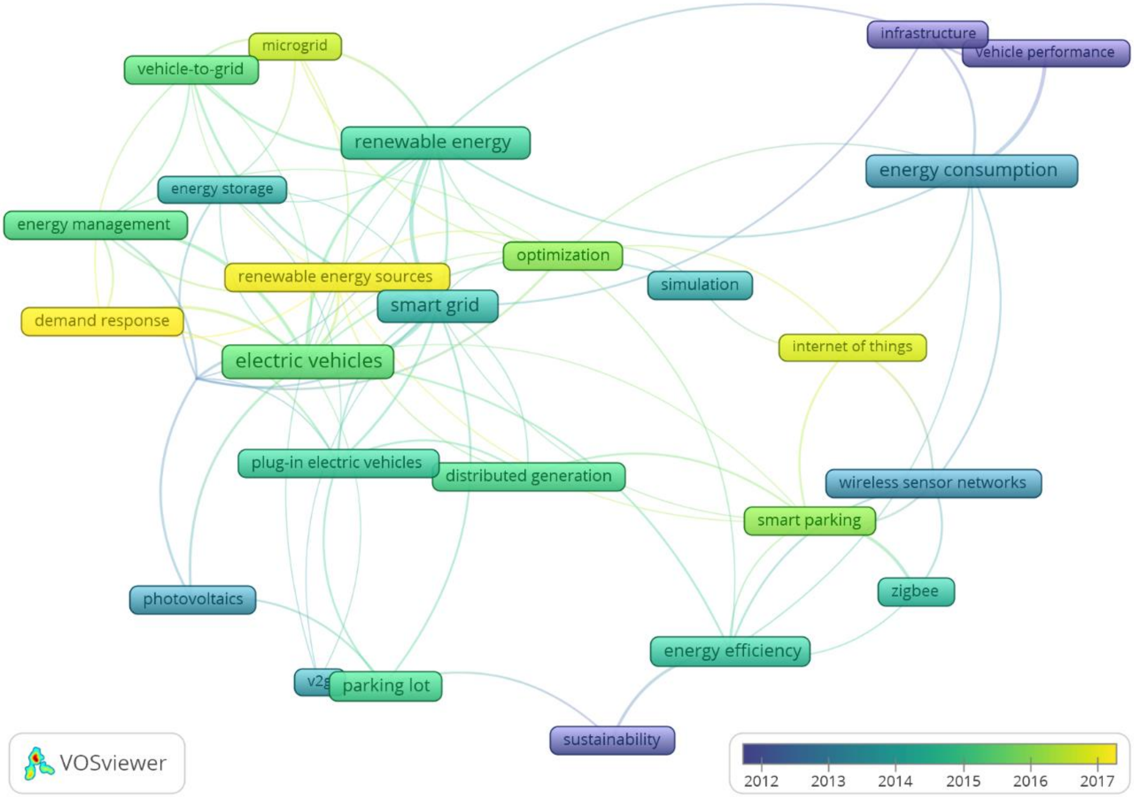


Figure 20 - Annual occurrence of author keywords about Energy Efficiency and Logistics Centers.

Each of these clusters can bring some light to the main problems and innovations in Energy Efficiency, related to the Logistics Centre sector.

The demand response, which consists in load shifting and peak shaving of energy demand aiming the lowest energy tariffs, the integration of distributed generated energy (PV) through smart grids with infrastructure demands and electric vehicles supply are some of the most discussed issues.

Zadek and Schulz (Zadek and Schulz 2011) discuss in their publication the sustainability aspects of Logistic Centres, emphasizing technologies for the use of local renewable energy sources (PV) to supply the infrastructure and transportation demands, including hydrogen (H_2) production for their forklifts. Bradshaw and David (Bradshaw and David 2010) show how a technologically advanced workplace is helping to reduce environmental impact and lower operating costs, using green building elements such as PV, a grey-water recycling system, and energy-efficient lighting.

Honarmand et al. (Honarmand, Zakariazadeh, and Jadid 2014) propose an energy resources management model for a microgrid in parking, arguing in favor of the integration of electric vehicles (EV) and the renewable energy source (PV), balancing the intermittent nature of PV generation and uncontrolled charging/discharging procedure of EV. In the same line, Tulpule et al. (Tulpule et al. 2013), also studies the economic and environmental impacts of a PV powered parking with charging station for EV. Rahmani-Andebili (Rahmani-Andebili 2016) studies the impacts of canopying EV parking lots with PV panels.

The internet of things (IoT) and the wireless sensor networks (WSN) are also in evidence. For example, Yang (Yang and Yang 2009) studies the connectionless indoor inventory tracking sensor network in Logistics Centers using an open source communication protocol for monitoring and control, named Zigbee RFID (Radio Frequency Identification). The use of WSN in buildings and warehouses for temperature measure, presence sense in lighting and ventilation systems are also some applications with energy saving purpose, discussed by researches as Seo et al. (Seo et al. 2015), Chang et al. (Chang, Yang, and Chou 2016) and Cho et al. (Cho and Jeong 2014).

The use of renewable energy sources, mainly PV connected to the grid and associated with batteries are analysed by Dávi et al. (Dávi et al. 2017), where they discuss the advantages and the restrictions that influence the feasibility of its implementation using modelling on EnergyPlus environment. In the same line, Kies et al. (Kies, Jurasz, and Dąbek 2018) study the use of PV and batteries but not connected to the grid.

Concerning the use of simulation tools for the calculation of PV solutions, the use of TRNSYS can be found in the studies of Villa-arrieta and Sumper (Villa-arrieta and Sumper 2018) linking the technical and economic variables. Also, Antoniadis and Martinopoulos (Antoniadis and Martinopoulos 2019) use this approach to optimize a solar thermal system.

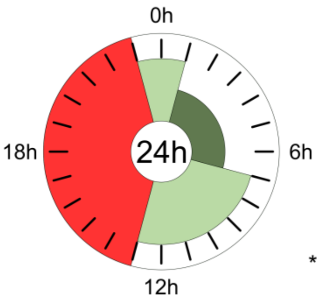
Publications mentioned above have made it possible to verify that energy efficiency studies for buildings using TRNSYS are well addressed in academia, although the most common modelling solutions are based on theoretical constructs or prototypes. The methodology novelty of coupling TRNSYS and other programs to optimize all the decision variables that are based on a real-life case study were motivations to produce and publish this work.

4. Materials and Methods

4.1. System description

This work includes the study of the electricity consumption of eleven units of the Logistics Centre (see *Figure 18*). The electricity in these units is consumed mainly for two different purposes: lightning and specific equipment operation, namely the energy consumed by the refrigeration chambers, the wastewater treatment equipment, and the pressure unit equipment. The total demanded energy is considered initially be obtained exclusively from the grid, and this situation will be our base case.

Every one of the eleven units has its consumption patterns and therefore, specifically contracted electricity and powers. All the contracts are made with Endesa S.A. for the “Tarifa Ahora” tariff of type 3.0A. This specific tariff is a low voltage tariff with three periods of charging (P1 – peak period, P2 – shoulder period and P3 – off-peak period). The prices of electricity and power charge for these periods are shown in *Figure 21*.

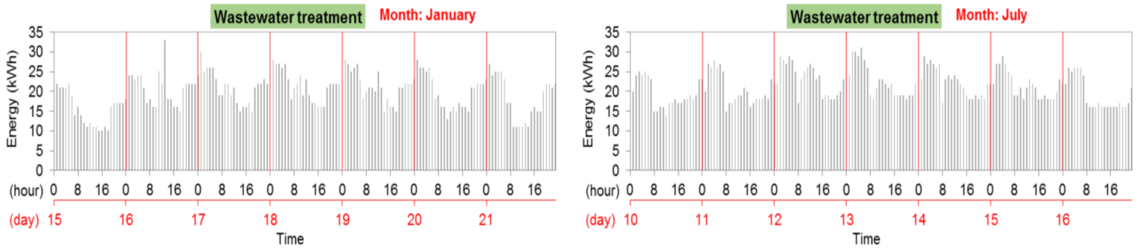


	Energy cost (€/kWh)	Power cost* (€/kW/day)
🟥 P1	0.109321	0.111586
🟩 P2	0.086337	0.066952
🟩 P3	0.059067	0.044636

* Charged monthly, according to the maximum demanded power at each period

Figure 21 - Schedule and respective costs of energy and power of the three periods of Endesa’s 3.0A tariff.

Below, in Figure 22, we present the typical weekly consumption profiles of some of the units of interest for two different weeks during a natural year (one week in winter, and another in summer). These profiles were built for the 11 units of the scope to evidence the season effect on energy consumption.



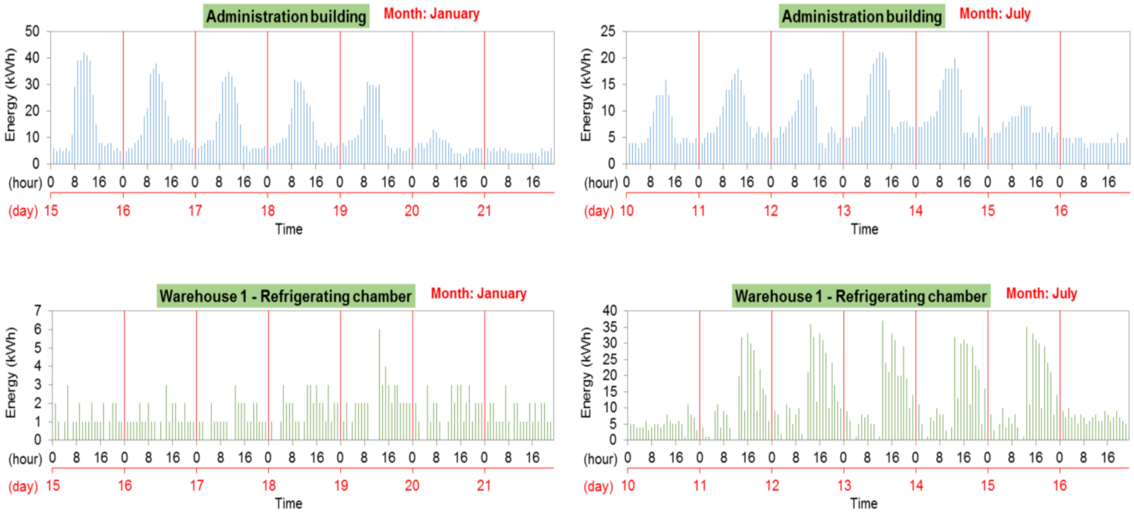


Figure 22 - Energy consumption profiles of some of the 11 units for two weeks of the year (January, 15-21 and July, 10-16).

The initially contracted powers for each unit of the study, *i.e.,* the base case contracts and the respective shares of P1, P2, and P3 are represented in Figure 23.

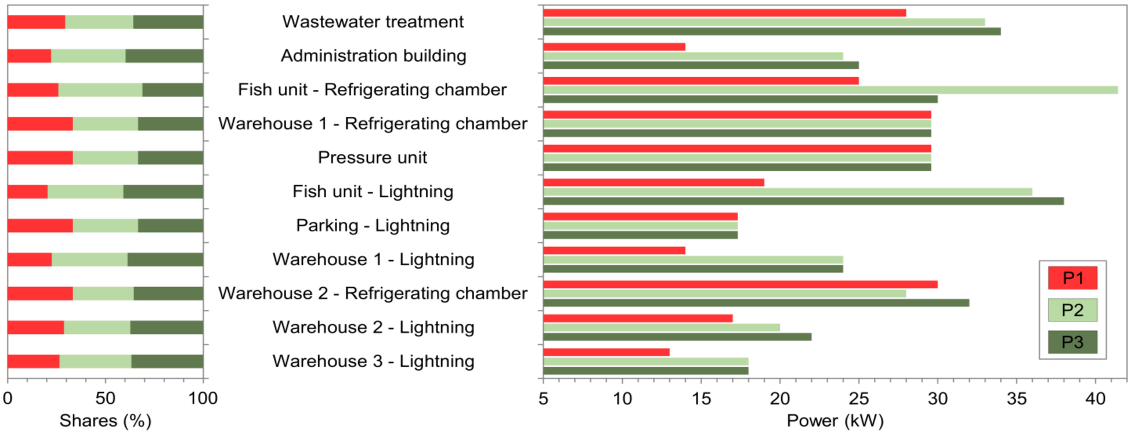


Figure 23 - Initial contracted power for every unit of the study (base case) and the shares of the three periods of Endesa's 3.0A tariff.

4.2. Modelling and simulations steps

The modelling for simulations was built using TRNSYS18 - Simulation Studio (University of Wisconsin-Madison 2004) and the metaheuristic algorithm based on particle swarm was performed by its optimization library component, GenOpt - Generic Optimization Program (Wetter 2011). The flowchart in Figure 24 describes the main steps for the integration of these tools. In this study, the files information exchange was done manually, although some automation can be implemented using numeric calculation software (e.g., MATLAB), as detailed by Tulus et al. (Tulus et al. 2016).

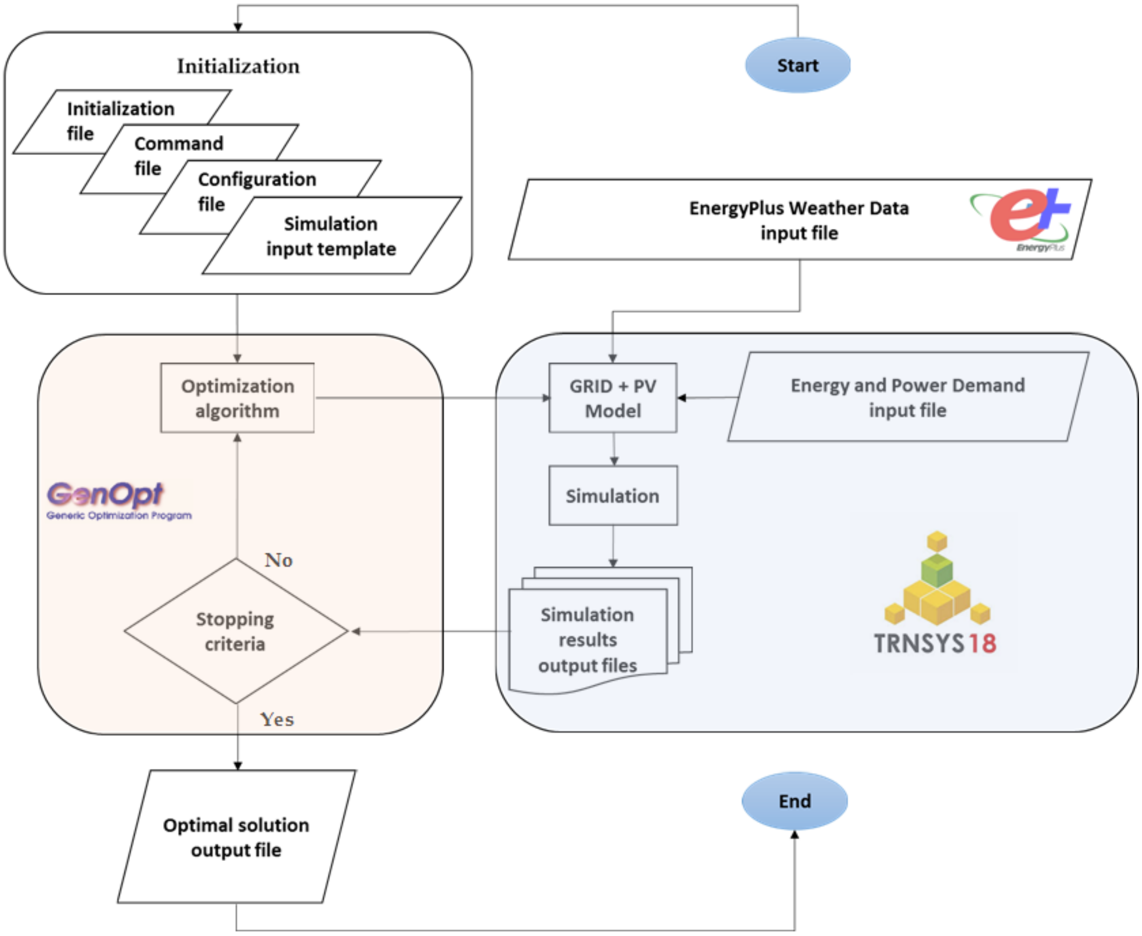


Figure 24 - Flowchart of modeling and simulation steps.

For modelling and simulation purposes were considered the available consumption profiles, the costs, and contracts as deterministic, i.e., representative as “typical” and invariable from year to year during the whole period of the study, that is, the life cycle timeframe of 20 years.

Four main steps could be made to achieve a reduction in the energetic expenses of the facility. They are: i) shift the consumption patterns towards the off-peak period; ii) optimize the individual contracts of the units by adjusting their contracted powers; iii) improve the energy efficiency by integrating the separate electricity contracts into one; iv) reduce the dependence on the grid by incorporating alternative energy sources.

In this study, we did not consider the option of shifting the consumption patterns towards cheaper periods of the tariff since we have no further knowledge about the companies operating in each unit of the Logistics Center. Therefore, the initial consumption profiles were taken as parameters, which could not be altered. The other three options, however, are quantitatively evaluated and discussed in the next sections. The quantitative evaluations have been performed based on the mathematical equations described below, aligned with the ASTM Standard Guide for Selecting Economic Methods for Evaluating Investments in Buildings and Building Systems (ASTM E1185 2014).

4.3. Mathematical procedures

4.3.1. Life Cycle Costing (LCC)

The economic estimations in this work are done based on the life cycle costing analysis method (ASTM E0917 2015b). This method includes all the discounted expenses originated during a specified time horizon of the facility's operation and had been used to analyze the feasibility of renewable energy solutions as showed by Naves et al. (Naves et al. 2018). The total discounted expenses are defined below as the net present cost (NPC [1]) of the project:

$$NPC = I_0 + CF_a \cdot PWF \qquad (1)$$

Where I_0 [2] is the capital investment in the start of the project (Equation 7), CF_a is the annual net cash flow detailed in Equation 3, and *PWF* is the present worth factor, which reflects the time value of money. The *PWF* (Equation 2) is the present worth of one Euro paid periodically in the future, where the nominal discount rate (d) and the time horizon of the analysis (N), in years, are considered.

$$PWF = \frac{1}{d}\left(1 - \left[\frac{1}{1+d}\right]^N\right) \qquad (2)$$

The annual net cash flow (CF_a), as defined in Equation 3, includes the annual costs of purchased energy (C_E [3]) and power (C_P [3]) in Euro (Equations 4 and 5) and the annual cost of maintenance (C_M [4]). The maintenance costs are considered only for action 3 (see section 2.5.3).

$$CF_a = C_E + C_P + C_M \ (3)$$

---

[1] Depending on the case study, *i.e.* any of the considered actions described in section 2.5, this variable may refer to one single unit or to the combination of all units of the Logistics Center.

[2] This variable may take the value of zero in case no investment is required.

[3] Depending on the case study, *i.e.* any of the considered actions described in section 2.5, this variable may refer to one single unit or to the combination of all units of the Logistics Center.

[4] This variable may take the value of zero in case no investment is required.

The annual energy costs are obtained as shown below in Equation 4, where E^3 is the annually consumed energy in kWh and C_E is the energy price in €/kWh (see *Figure 21*). Both E^3 and C_E vary depending on the index (*i)*, which represents one of the charging periods of the 3.0A tariff specified in Figure 21.

$$C_E = \sum_i E_{(i)} \cdot c_{E(i)} \quad \forall i \in \{P1, P2, P3\} \tag{4}$$

The annual power costs are calculated in Equation 5. There, D represents the cardinal number of days in a specific month m, $P_{ch}{}^3$ is the monthly charged power in kW and C_P is the power price in €/kW/day. As in the previous equation, $P_{ch}{}^3$ and C_P vary depending on the charging periods of the 3.0A tariff (*Figure 21*) and the charged power may vary from month to month as well.

$$C_P = \sum_i \sum_m D_{(m)} \cdot P_{ch(m,i)} \cdot c_{P(i)} \quad \forall i \in \{P1, P2, P3\} \text{ and m} \in \{\text{12 months of a year}\} \tag{5}$$

A piecewise function in Equation 6, defines the charged power ($P_{ch}{}^3$). This function is split in ranges depending on where the maximum demanded power of a specific month ($P_d^{max\,3}$) falls concerning the contracted power ($P_c{}^3$).

$$P_{ch} = \begin{cases} P_d^{max}, & \text{if } 0.85 \cdot P_c \leq P_d^{max} \leq 1.05 \cdot P_c \\ 0.85 \cdot P_c, & \text{if } P_d^{max} < 0.85 \cdot P_c \\ P_d^{max} + 2(P_d^{max} - 1.05 \cdot P_c), & \text{if } P_d^{max} > 1.05 \cdot P_c \end{cases} \tag{6}$$

The investment capital (I_0) in this study is present only in action 3 (see section 2.5.3) when photovoltaic panels have to be purchased. I_0 is defined as follows:

$$I_0 = n_{PV} \cdot P_{PV} \cdot C_{PV} \tag{7}$$

In Equation 7 the n_{PV} is the number of installed photovoltaic panels, P_{PV} is the power supplied per panel in Wp/panel, and C_{PV} is the PV price in €/Wp.

4.3.2. Discounted Payback Period (PBP)

One conventional technique of preliminary economic viability evaluation of a project is the payback period (PBP) (ASTM E1121 2012). PBP is usually defined as the time required for recovering the initial capital investment (I_0). In this particular work, the discounted payback period ($_dPBP$) was considered using Equation 8, where negative I_0 is the capital investment in the start of the project (Equation 7) and $_dS_t$ are the discounted savings in period t summed throughout years between 1 and $_dPBP$.

$$-I_0 + \sum_{t=1}^{dPBP} dS_t = 0 \tag{8}$$

The discounted savings (Equation 9) can be obtained from the actualization of the annual savings of a particular project with an implemented action (see proposed actions in section 2.5). Those annual savings are the difference between the annual cash flows of the base case, *i.e.,* current situation, and the cash flows of the proposed action. In Equation 9 the base case cash flows are referred to with "*" symbol.

$$dS_t = \frac{CF_a^* - CF_a}{(1+d)^t} \qquad (9)$$

According to Equation 8, the ${}_dPBP$ for actions 1 and 2 will be zero, since no investment costs are required for their implementation.

4.4. Optimization Models

Model M-1 is used to obtain the minimum *NPC* of every unit of the Logistics Center for action 1 (see details in section 2.5.1). This model minimizes the *NPC* of a Logistics Center unit, subject to Equations 2 to 6, by varying the contracted powers (P_c) (one for each charging period of the 3.0A tariff) between the specified lower (P_c^L) and upper (P_c^U) bounds. Later on, the minimum NPCs are added up to represent the total net present cost of the project over the analysed timeframe.

$$\min_{P_{c(i)}} NPC \text{ (Eq. 1)}$$

$$\begin{aligned}\text{s.t. } & \text{Eq. 2 to 6} \\ & P_c^L \leq P_{c(i)} \leq P_c^U \\ & P_{c(i)} \in \mathbb{R} \quad \forall i \in \{P1, P2, P3\} \qquad \text{(M-1)}\end{aligned}$$

Likewise, model M-1 is used in action 2 (see details in section 2.5.2), but in this case, the minimized *NPC* represents the combined cost of all units studied in this project. Equations 2 to 6 and the lower (P_c^L) and upper (P_c^U) bounds are conveniently modified to correspond to the combination of the units.

Due to the nonlinearities of the model M-1, it is solved using the TRNSYS18 - Simulation Studio (University of Wisconsin-Madison 2004) and its optimization library component, GenOpt - Generic Optimization Program (Wetter 2011) in a Single-Objective Optimization (SOO) process based on the NPC with an LCC perspective. This approach can be found in similar studies using Multi-Objective Optimization (MOO) processes as performed by Li et al. (K. Li et al. 2017) and Asadi et al. (Asadi et al. 2012).

Finally, model M-2 is implemented for action 3 (see details in section 2.5.3) where *NPC* is minimized subject to Equations 2 to 7 and additional energy balances provided by the simulation software. The decision variable in model M-2 is the number of PV panels, which are decided to be installed in strings of 7 individual panels connected in series. This distribution is advisable for security purposes and to adequate the DC voltage to the input range of market inverters (e.g., Solar Inverters List published by NATA – National Association of Testing Authorities (NATA Accredited Laboratories 2019)).

Due to the strong nonlinearities of the optimization model M-2, which additionally contains implicit equations evaluated by the simulation software, the model is solved using a metaheuristic algorithm based on particle swarm implemented in the optimization tool, GenOpt (see Figure 24).

$\min_{n_{PV}} NPC$ (Eq. 1)

s.t. Eq. 2 to 7

energy balances

$\mathrm{n}_{PV}^{L} \leq n_{PV} \leq n_{PV}^{U}$

$\mathrm{n}_{PV} \in \mathbb{N} : 7 \mid n_{PV}$ (M-2)

4.5. Case studies

As mentioned in the previous section, we have developed three different case studies, three possible actions whose implementation is to be evaluated by the decision makers. These actions are detailed below and, for the sake of comparison of the results among them and the current situation, a base case is introduced as the current operation state of the Logistics Centre in section 2.1.

4.5.1. Action 1: Optimization of individual contracts

This action, in theory, would not require additional expenses for the company. The only required action would imply the revision of each of the current contracts according to the optimization results provided in section 2.1.

4.5.2. Action 2: Optimization of combined contracts

In action 2 we suggest considering the possibility of a combination of the eleven separate electricity contracts into one contract.

4.5.3. Action 3: Integration of photovoltaic panels

The integration of renewable energy sources can suppose a significant profit, but as opposed to the previous two actions, an initial investment is required.

However, over time, the savings can potentially be more significant and, on top of that, it can have multiple environmental benefits.

Action 3 would imply the integration of photovoltaic (PV) panels in order to reduce the dependence on the grid. For this case study, the energy demand of the separate units was considered as one combined demand (as in action 2) which would be partially covered by the PV panels (the grid will provide the rest).

Since the sector of solar energy rapidly evolves, the PV technology, its efficiency, performance, and cost regularly change. For that reason, we have considered three scenarios reflecting the aspect of the price of the PV panels, cPV, (given in Euro per peak Watt, which includes the module itself, the structure and the installation costs):

- Scenario A – low cost, represents 0.68 €/Wp;
- Scenario B – intermediate cost, represents 1.18 €/Wp;
- Scenario C – high cost, represents 1.48 €/Wp.

The maintenance costs (cM) in each of the three scenarios are considered to be 0.02 €/Wp/year.

4.6. Assumptions

Below is presented the set of additional assumptions and simplifications considered in this work, but not mentioned earlier.

The adopted electricity tariffs were based on the electricity bills of 2017, Endesa "Tarifa Ahora" type 3.0A (see *Figure 21*). The available consumption profiles are considered "typical" and invariable from year to year during the whole period of the study. For the net present cost (*NPC*) calculations were adopted annual values for the discount rate of 2.00% and energy prices in constant euros. The time horizon of the analysis (*N*) was 20 years (expected lifetime of the PV system). The simulation model includes hourly based climatic data of Spain obtained from EnergyPlus Weather Data (Energy Plus 2018) and a data file covering a natural year of energy consumption and power demand (8760 hours).

According to a publication from NREL (National Renewable Energy Laboratory) (Jordan and Kurtz 2012), the polycrystalline silicon PV panels output power drops in average 0.5% per year. It means that in a timeframe of 20 years the power output of a PV panel would decrease 9% and if considered a rated efficiency of 14.7% (SHARP

2019a), an efficiency drop of 1.3%. These number are based on previous work, as those performed by Kitamura et al. (Kitamura and Takakura 1997), however the lack of historical data related to most recent manufactured PV panels (with improved efficiency rates) and doubts about the non-linearity of the lifespan efficiency degradation rate, led the authors to avoid including this factor on the calculations.

The average efficiency of the PV panels for this case study is 11.7%, with a module efficiency of 13.4% and inverter efficiency of 91.5%. Each single-panel occupies a surface of 1.64 m2 and must be connected in parallel sets of 7 panels each (the separate sets are connected in series). The complete list of the PV specifications can be found in (SHARP 2019b) and the main electrical specifications used to configure the PV component (type 190) on TRNSYS model, according to the calculation method presented by DeSoto et al. (De Soto, Klein, and Beckman 2006), are described in Table 4.

Table 4 - Main PV electrical specifications

PV Electrical specifications	
Cell	156.5mm. Square Polycrystalline silicon
No. of Cells and Connections	60 in series
Open Circuit Voltage (Voc)	36.5V
Maximum Power Voltage (Vpm)	29.2V
Short Circuit Current (Isc)	8.20A
Maximum Power Current (Ipm)	7.54A
Maximum Power (Pmax)*	Typical 220W
Encapsulated Solar Cell Efficiency (ηc)	15%
Module Efficiency (ηm)	13.4%
Maximum System Voltage	DC 1000V
Series Fuse Rating	15A
Temperature Coefficient (Pmax)	- 0.485 %/˚C
Temperature Coefficient (Voc)	- 0.13 V/ ˚C
Temperature Coefficient (Isc)	- 0.053 %/˚C
** (STC) Standard Test Conditions: 25˚C, 1 kW/m2, AM 1.5*	

5. Results

In Figure 25 are presented the summarized results of the three proposed actions of this study and the current state (base case) in terms of (total) net present cost and amount of electricity consumption.

While Action 1 and Action 2 does not require essential equipment investments, consisting mainly in review the contracts and the connection configuration between the loads and the grid (Electrical Company issues), the Action 3 requires special attention, to avoid oversizing of the PV.

Also, in Figure 25, the adverse effect in the LCC due to the oversizing of the PV panels in Action 3, can be verified if we move from the right to the left side on the plotted points of scenarios A, B, and C.

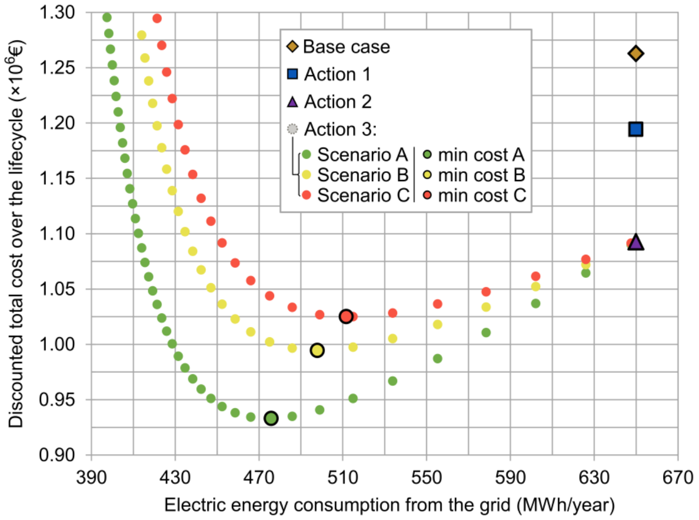


Figure 25 - Summary of proposed actions and base case, i.e., the current situation of the Logistics Center.

The right side of the highlighted optimal points A, B and C represents the region where the increasing of PV panels corresponds to an LCC reduction. The left side represents the region of oversizing, where an increase in PV panels increases the total costs, meaning the unfeasibility in an LCC perspective unless an appropriate use for the surplus energy is addressed, as commented above (see section 1).

Action 1 represents 5.43% of cost reductions after revising the contracted powers for each separate unit of the study. In the same direction, action 2, maintaining the same energy consumption from the grid as the action 1 and the base case, achieves a reduction of up to 13.47% in cost (compared to the base case). Recall that action 2 would imply the combination of the demands of all units into one combined demand.

A more detailed annual cost (i.e., annual cash flows) breakdown of actions 1 and 2 can be found in Figure 26 and the changes to be implemented are shown in Figure 27.

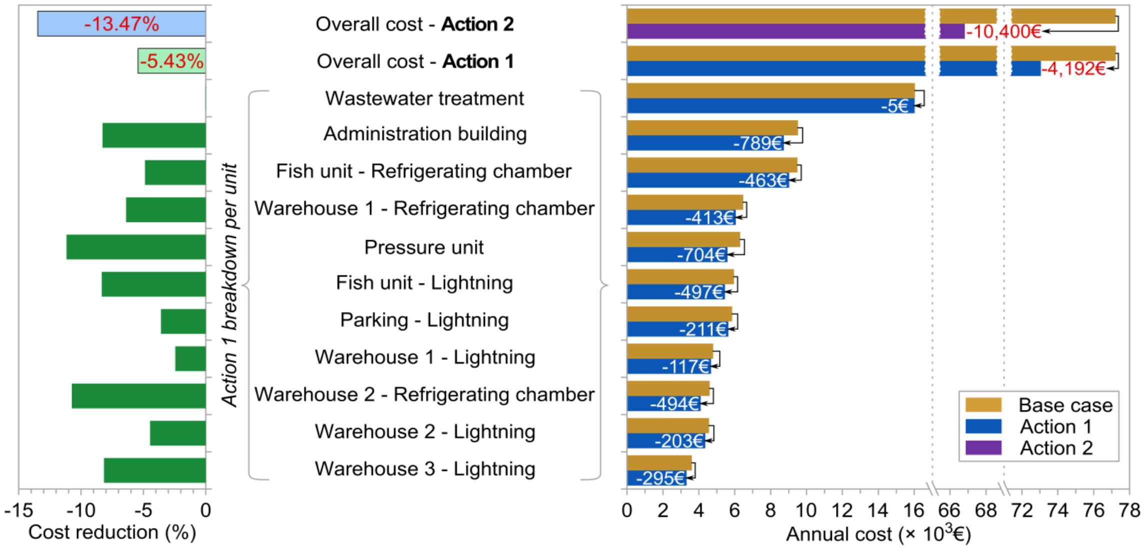


Figure 26 - Breakdown of action 1 and 2 compared to the base case.

Action 3, and more specifically its optimal scenario A (see *Figure 25*) can present as much as 26.13% cost reduction compared to the base case. This solution would also contribute to 26.8% to the reduction of grid dependency. The other scenarios and their optimal and suboptimal solutions can also potentially provide cost reductions over the lifecycle of the study.

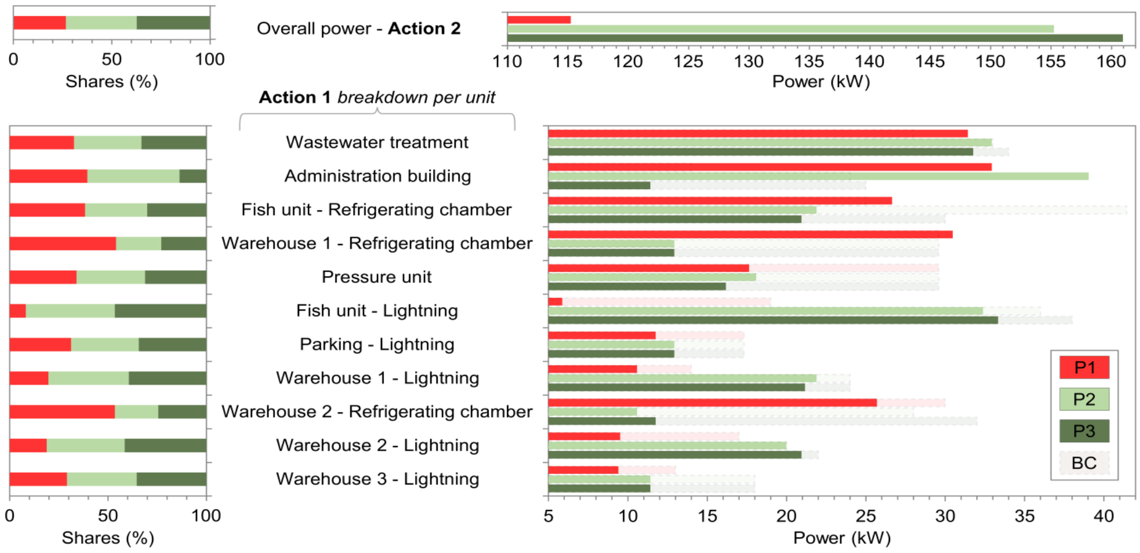


Figure 27 - Optimized power per unit for action 1 compared to the base case (BC, i.e., current situation), overall optimized power for action 2 and their relative shares depending on the three periods of Endesa's 3.0A tariff.

6. Discussion

As shown in section 3, an oversizing of the PV field would increase the total cost significantly, while the reduction in energy consumption is marginal.

The cost breakdown of action 3 and scenarios A, B, and C are shown in *Figure 28*a. Here the cost is presented as a function of the number of PV panels. The colored square points correspond to the investment cost of PV, the grey triangle points are the electricity costs billed by the electricity provider (Endesa in this case), and the colored circle points show the overall life-cycle cost, *i.e.,* the summation of the PV investment and charged grid electricity.

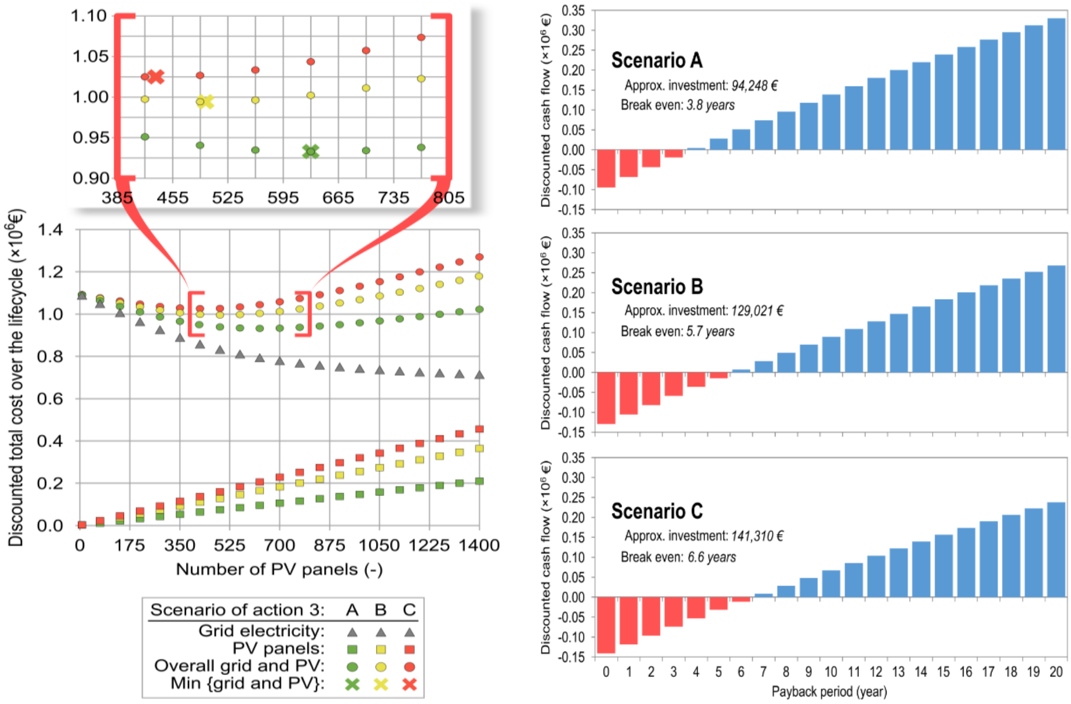


Figure 28 - (a) Breakdown of action 3 including its 3 scenarios. (b) Discounted PB period for the3 scenarios of action 3.

The zoomed area indicates the optimum solutions for scenarios A, B, and C. The optimal number of PV panels to be installed for each scenario is 630, 497, and 434. Making a rough approximation of the area which would be occupied by these panels, it is obtained 1035 m^2, 816 m^2 and 713 m^2 for every particular optimal solution of scenarios A, B, and C.

The scenarios mentioned above are feasible to implement since the total rooftop available area of the industrial units is around 24,200 m^2 (3 units with 5,000 m^2 each; 3 units with 3,740 m^2, 2,040 m^2 and 1,830 m^2 respectively; 1 Commercial unit with 570 m^2; 1 Administration unit with 940 m^2). The parking area corresponds to 25,830 m^2, representing an option to implement PV panels coverages (canopy).

Action 3 would require an initial investment, which will strongly depend on the assumptions described in section 2.6. At this moment the investment costs and payback periods are presented in *Figure 28*b.

Depending on the cost of the PV panels, the investment cost and break-even point will vary significantly, so precautions must be taken while defining the PV cost mentioned above.

7. Conclusions

The three actions proposed in this study could potentially conduct to savings of different importance subject to the described simplifications and assumptions. Further investigations in any of these directions would be required to provide more detailed results and indications.

However, 5.43% cost reduction could be achieved by the implementation of slight changes to the contracted power for every separate contract. Higher cost reduction, up to 13.47%, could be reached in case of unification of the contracts. In the previous two cases, no significant additional investment costs would be required.

As we also aimed to show, if significant investments are taken in a life-cycle perspective (LCC), their feasibility can be unveiled. To attain higher cost reductions in long-term (up to 21% in the intermediate case, action 3 scenario B) and at the same time to reduce the consumption of electricity from the grid around a quarter, an investment of 129,000€ would be needed, which is expected to pay-off in less than six years.

Any other lower improvements can hypothetically be achieved with fewer investment costs and smaller payback periods.

IV – Case Study II - Integration of renewable energy and thermal energy storage in residential buildings

For the energy balance analysis, the definition of the systems clearly establishing their physical frontiers and the time frame can bring the most different and, in some cases, controversial results. With this consideration, the zero-energy balance, applied for buildings can be achieved by the tuning of the energy efficiency of their most energy consuming systems and improving their autonomy in relation to external energy sources, expanding the borders of the system to the whole building.

Our objective is to show that the cooling systems, for tropical climate located buildings, as one of the most energy consuming systems can have their efficiency increased if associated with photovoltaic panels (PV) and thermal energy storage systems (TES). A literature review was conducted to determine the state of the art and to establish a baseline for our studies. A hypothetical building was configured with detailed loads and systems to simulate different configurations of an air-cooled chiller associated with PV and TES.

Using the TRNSYS18 Simulation Studio, a set of scenarios were simulated, and their outputs analysed in a life cycle perspective using Life Cycle Costing (LCC) for the calculations. The simulations consisted of variations in sizing and operability of the systems and generated results that validate our proposition toward a zero-energy building, using input data and parameter from manufacturers and standardized level of comfort for the building occupants to generate the feasible scenarios.

The modelling and simulation of different scenarios allowed envisage the most economic configurations for buildings in a life cycle perspective, though the LCC reduction within a safe range of operability considering the energy efficiency and consequently the sustainability aspects of buildings. The results can be used as premises for initial design or for planning retrofits of the buildings, aiming the zero-energy balance.

1. Introduction

Aiming to conduct an optimization study of the space cooling systems, the TRNSYS18 Simulation Software was used to modelling a building and its main load components. The simulations were conducted shifting the energy consumption of the cooling system to the off-peak periods and then using a thermal energy storage (TES) to attend the cooling demand during the peak periods. A central air chilled system was configured associated with a TES using water as energy storage element. The 3D building model was done through the Sketchup Software and exported to the TRANSYS18 using an integration plugin.

Analyses of hourly based, annual climate data from three cities in Brazil allowed to verify the solar thermal effects in the buildings at different latitudes (1º, 23º and 31º Latitude South), even beyond the tropic latitude limit.

Different scenarios were simulated, and the analyses of the results allowed to obtain savings in energy consumption cost up to 15% and a reduction of the power configuration circuits and equipment up to 50%. In a life cycle perspective, the results emphasize the sustainability of the adopted solutions. The use of solar energy to supply the peak periods demand is also considered in this energy efficiency model.

The methodology to implement the simulations, the case study details and the main results and conclusions are presented in this paper.

2. Methodology

2.1. Energy efficiency study framework

As stated by Schneider (F. Schneider 2014) and previously endorsed by Rudestam and Newton (Rudestam and Newton 2007) , the methods are the practical hands-on steps for doing a study and the methodology is the discussion of these methods. The methods usually include defining the scope of the research project, coming up with a research question or hypothesis, selecting and collecting data, processing that data with certain tools to enable analysis, and then going through the data systematically to answer the central question.

The requirements mentioned above were organized into a Framework aiming to stablish a comprehensive structure of the main steps adopted to reach the results of this study and their distribution in the whole document.

Based on the framework, the application to this study about Energy Efficiency aspects are detailed in Figure 29, before to explain in more details at the topics case study, results, discussion and conclusion.

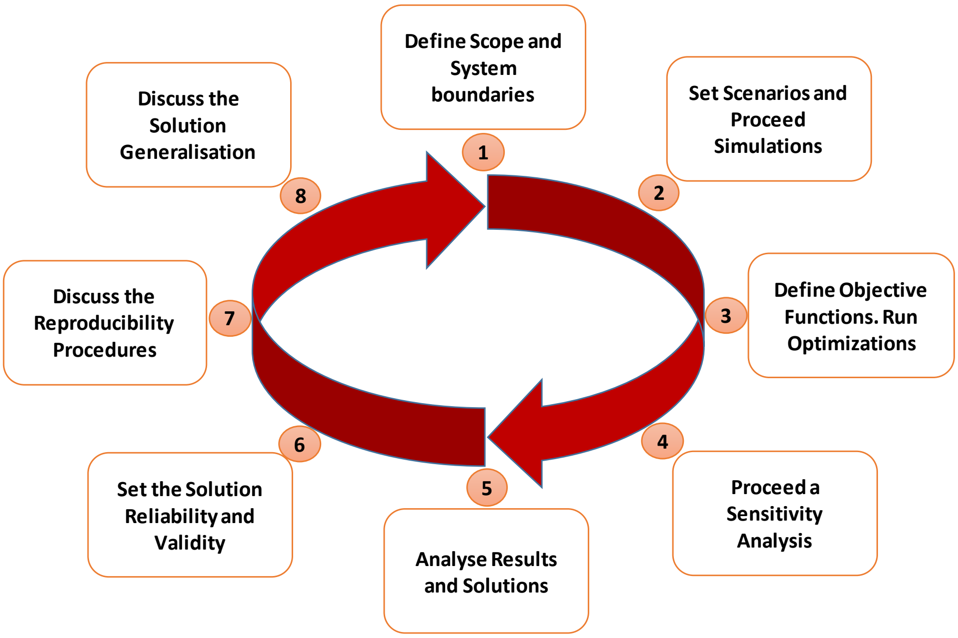


Figure 29 - Framework for energy efficiency analysis

Life cycle perspective though the application of Life Cycle Cost (LCC) allows the comparison of different scenarios extending the period analysis beyond the initial investments and can unveil the trade-offs necessary to justify the decisions. The Payback period can also support the decision-making process.

The results of modelling, simulation and optimization can support an eventual design phase of the feasible solutions and foreseen advantages, disadvantages, restrictions and opportunities with technological and economic aspects in a life cycle approach. Here we present the main methods (tools) that support this study, the reasons of its adoptions, the way they were applied and how they can be reproduced.

2.1.1. Modelling and simulation scenarios

Due to the characteristics of the object of study, mainly because of the existence of a great number of independent variables, the use of equations relating the systems variables has an excessive computational time consuming. However, the use of simulation software based on numerical calculation of models of well know systems (e.g. buildings and its facilities) allows the analysis of these models. By these reasons, TRNSYS 18 Simulation Studio and its optimization library component, GenOpt - Generic Optimization Program, were chosen.

The modelling of the scenarios in TRNSYS 18 uses modules, named types, which represents the main systems.

For the energy efficiency studies, three models were configured and integrated at TRNSYS 18. The integration is a prerequisite to run the optimizations of the complete model by GenOpt.

First, a hypothetical Building Model was designed in order to obtain the electrical energy demand based on three main loads, that is, the cooling, the lightning and equipment energy demand. The building electrical energy demand from lightning and equipment was obtained from standard load and occupation configuration, directly on the TRNSYS Type 56b.

After that, the building electrical energy demand from cooling was obtained through the cooling demand necessary to maintain the comfort of the apartments that was used as input to the Chiller/TES Model. This model allows to obtain detailed data from each of the ASHRAE operational modes electrical energy demand and change these operational modes during the optimization process.

Finally, the PV/GRID Model was designed to allow the simulations and optimizations of the different configurations of PV and GRID as the supply of electrical energy, considering the three main loads electrical demand obtained from the other two TRNSYS models, which the connection schema can be seen in Figure 30. Note that type 9c described at the same figure, is the integration point between this model and the other two models, reading the electrical energy demand from the building.

The types used to build the TRNSYS models are briefly described below, with some specific characteristics, to justify their utilization, and also help the reader eventually reproduce their functionalities in similar modelling studies:

- Type 15-2: Weather Data Processor.
    - Combines data reading, radiation processing and sky temperature calculations.
    - Energy Plus Weather Data (Energy Plus 2018) from different locations (Brazil) in an hourly base for one year were used to simulate the solar energy potential as input for the PV Array.
- Type 56b: Building.
    - Aggregates the information from the building model drawn in the Trimble Sketchup2016 Software and exported via 3DTrnsys plugin to TRNSYS18 Simulation Studio from the Thermal Energy Systems Specialists.
    - At TRNSYS18 the building was represented in the Simulation Model as a Type56b component, composed by zones, defined during the drawing phase, connected with other types, such as weather information, unit calculation and conversion tools, printers, plotters, cooling/heating systems, thermal energy storage and grid energy tariffs information. Building location (hemisphere, position) inputs and outputs were defined also in the Type56b via TRNBuild Editor, and each building zone, named air node, was configured as an apartment, to allow the configuration of construction types (walls, floors, ceilings, roofs, windows, doors), scheduling (occupation, control of regime types

components), and the regime types (infiltration, ventilation, heating, cooling, comfort, gains, losses, lightning and daylight controls). These configurations can be implemented specifically for each zone or as a common parameter. The energy demand of the building, considering the cooling demand, lightning and equipment were imported by the PV model, via Type 9c, as mentioned above and shown at Figure 30.

- Type 9c: Data Reader for Generic Data Files.
    - Serves the purpose of reading data at regular time intervals from a data file, converting it to a desired system of units, and making it available to other TRNSYS components.
    - It was used to read the electrical hourly energy and power data files.
- Type 190d: Photovoltaic (PV) Array with Maximum Power Point Tracking (MPPT) and Inverter (Direct Current to Alternate Current).
    - Determines the electrical performance of a photovoltaic array, based on the calculation method presented by DeSoto et al (De Soto, Klein, and Beckman 2006).
    - Different array configurations categorized into scenarios were simulated in order to attend the building energy demand.
- Type 14h: Time Dependent Forcing Function.
    - Employs a time dependent forcing function, which has a repeated pattern. Discrete data points indicating the value of the function at various times throughout one cycle (e.g. one day) set the pattern of the forcing function.
    - It was used to set the Variable Tariff Schedule for the energy and power contracted in order to calculate the costs and proceed the life cycle cost and payback optimizations for the different scenarios.
- Type 24: Quantity Integrator.
    - Integrates a series of quantities over a period. Each quantity integrator can have up to 500 inputs. It is able to reset either periodically

    throughout the simulation or after a specified number of hours or after each month of the year.

    - It was used to summarize the amount of energy consumption, power demand and life cycle costing.

- Type Equation: Algebraic, Logic and Boolean Equations.
    - Allows implementing calculations and formulas using equations.
    - It was used to calculate the output integrated values from Type 24 (Integrator) and to implement logical conditions for the different scenarios related for example to the use of Solar Energy or Grid Energy to attend the energy consumption and power demand. Also used to calculate the life cycle costing and payback period of possible investments for each scenario.
- Type 25a: Printer – TRNSYS.
    - Supplies units printed to an output file.
    - Allowed to export the simulation and calculation results.

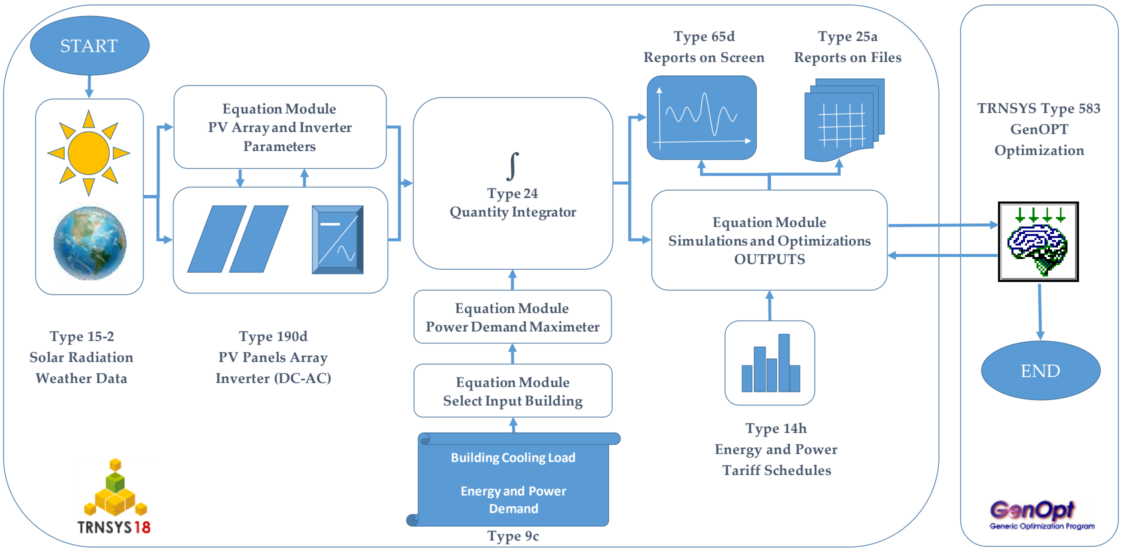


Figure 30 – TRNSYS model for Energy Efficiency simulations and optimization

Different scenarios were simulated and based on the principles of Life Cycle Costing (LCC) and Payback Period, the GenOpt performed multi-objective optimization (MOO) process, taking into account the life cycle economic aspects. The GenOpt Plugin can read its input from text files generated by TRNSYS 18 simulations and writes its output to text files. The independent variables can be continuous variables (possibly with lower and upper bounds), discrete variables, or both, continuous and discrete variables. Constraints on dependent variables can be implemented using penalty or barrier functions. GenOpt uses parallel computing to evaluate the simulations.

TRNSYS Model considers also the surplus energy, produced by the PV but not consumed by the loads, due to the exceeding production during the periods of most intensive solar radiation. An electricity tariff can be attributed to the surplus energy exported to the GRID, that will reflect positively on the cost savings calculation and consequently in the LCC and Payback period of the investments. The storage of the PV surplus energy and its use in other periods can also be simulated. PV array physical space demanded which can represent a restriction for the PV installation on the rooftops or in the parking, is also obtained by the simulations and the optimization process.

In order to run the simulations, besides the data requirements described above for each Type Module in TRNSYS some scenarios were considered, and some restrictions were taken into account. The three mail loads of the building were the chiller, lightning and equipment. The integration of the TES and chiller, running on each of the four ASHRAE operational modes, and PV connected to the GRID, allowed to identify the scenarios described below and to obtain the optimal configuration through the simulations and optimization process.

At the TRNSYS Model were configured a forcing function in order to select the ASHRAE operational mode for the chiller and TES and also to switch the integration of PV and the GRID for simulation and optimization.

- Base Case GRID + Chiller
- Scenario 1 GRID + Chiller + TES (Full Storage Load)
- Scenario 2 GRID + Chiller + TES (Load Levelled)
- Scenario 3 GRID + Chiller + TES (Demand Limiting)

2.1.2. Data requirements, objective functions and optimization assumptions

The simulation data collected in an hourly base allows the direct calculation of power (kJ/h or kW) and energy (kJ or kWh). These data were used as input to the Central Cooling System based on Air-cooled Chiller and the Thermal Energy Storage (TES). The electricity from the grid was used to supply the energy demand integrated with the solar photovoltaic panels.

Weather data files from different cities were obtained from the US National Renewable Energy Laboratory (NREL) web site. The simulation graphics can be built for different time frames, up to 8760 hours (1 year), as showed in **Figure 31**, allowing to verify the cycling seasons effect on the building temperature, cooling/heating demand compared to the external weather conditions, or 24 hours, used for the energy consumption shifting calculations.

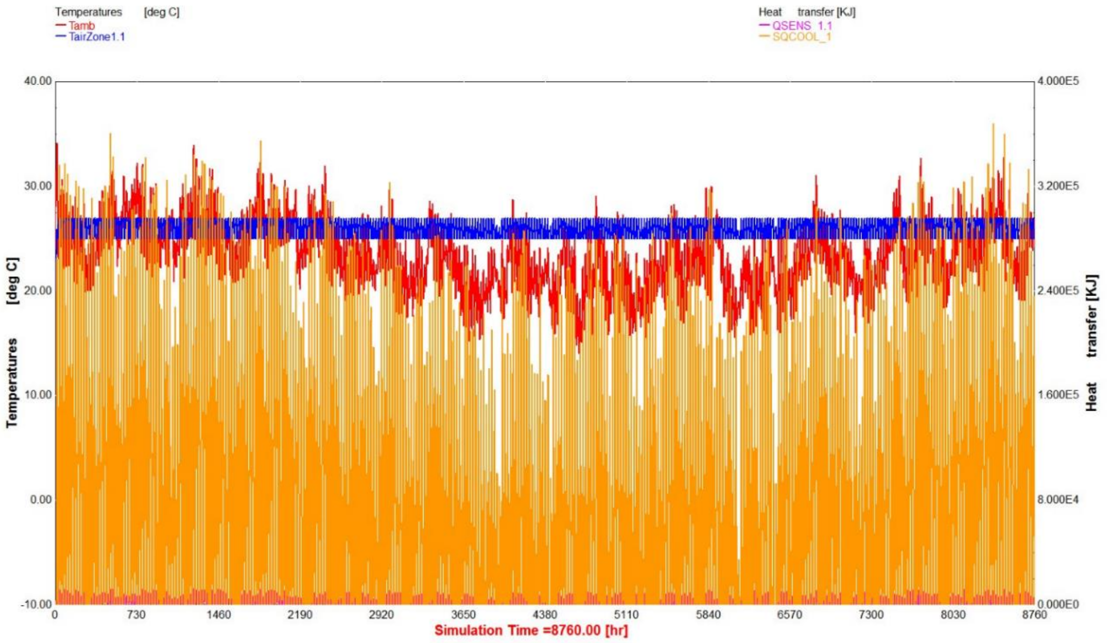


Figure 31 - Annual Simulation with ambient temperatures (red), comfort inside temperatures (blue) and cooling demand (orange)

2.2. Energy efficiency and mathematical concepts

2.2.1. Demand Response (DR)

The US National Action Plan on Demand Response (The Federal Energy Regulatory Comission Staff 1993), explains DR as a reduction in the consumption of electric energy by customers from their expected consumption in response to an increase in the price of electric energy or to incentive payments designed to induce lower consumption of electric energy. In their studies, Li et al. (W.-T. Li et al. 2015), arises the potential of DR schemes to manage energy for residential buildings in a smart grid context. However, the DR has as one of its main prerequisites the implementation of Advanced Metering (AM), known as that measure and record usage data at hourly intervals or more frequently, providing usage data to both consumers and energy companies at least once daily (Parker et al. 2015).

In these studies, the DR was adopted, simulating the effects of shifting the cooling energy consumption from the peak to the off-peak tariff hours. The main goal of the simulations was to find the operation energy rate and lowest cost. The power was also one of the main simulation results, not only for its weight on the sizing of the cooling system and electrical circuits but also because of its considerable part on the electricity tariffs.

After the Base Case definition, four scenarios and solutions, concerning the cooling systems, were simulated to optimize the cooling energy production during the off-peak periods and storing it to attend the building cooling demand during the peak periods. At Figure 32, are shown the energy tariff used for the calculations. The variable tariff (hours of the day, seasons of the year) has been adopted by several countries. The Spanish Seasonal Tariffs, for example, is already implemented and the Brazilian White Tariff for residential customers has been implemented in 2018, according to the Brazilian National Electrical Energy Agency (Brazilian National Electrical Energy Agency 2017).

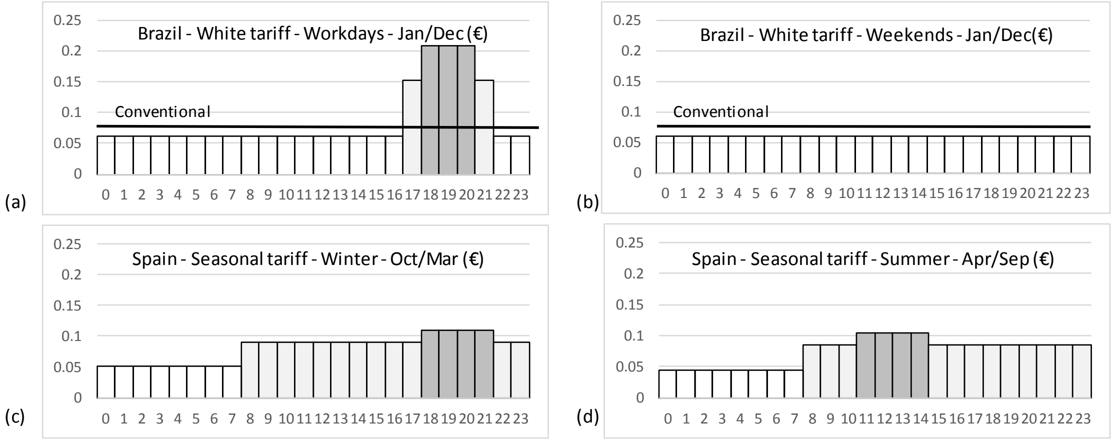


Figure 32 - Electricity tariffs – Brazilian White Tariff

As pointed out by Sehar et al. (Sehar, Pipattanasomporn, and Rahman 2016), the cool energy can be stored in Thermal Energy Storages (TES) in form of ice, chilled water, eutectic solution or phase change materials during the night times and used in the daytime. Parameshwaran et al. (Parameshwaran et al. 2012) and Heier et al. (Heier, Bales, and Martin 2015) explains in their studies the most important strategies for charging and discharging a TES to meet cooling demand during peak hours: full-storage and partial-storage strategies.

The choice of the strategy is based on the characteristics of the cooling load. This approach was adopted also for the Air Chilled Cooling System for the simulations, aiming the energy savings and operational optimizations, foreseeing also the electrical power sizing and the equipment's service life, without compromise the building cooling demand. The choice for a chilled water-based TES, despite its lower costs and good efficiency rates, was also influenced by the results described by Hasnain (Hasnain 1998) in a recent review publication.

2.2.2. Life Cycle Costing (LCC)

The LCC basic calculation formulas are presented in the Equations 4 and 5. The Present Value of LCC, named PVLCC was adopted for the comparison of the different scenarios and as the decision support tool, calculated as follows.

$$PVLCC(t,i,C) = \sum_{t=0}^{N} \frac{C_t}{(1+i)^t} \qquad (4)$$

Where:

Ct = Sum of all relevant costs occurring in year t [€];

N = Length of study period [years];

i = Nominal discount rate.

The nominal discount rate (i), considering the inflation rate (I) was calculated as shown at Equation 5.

$$i = (1 + r).(1 + I) - 1 \tag{5}$$

Where:

r = real discount rate;

i = nominal discount rate;

I = general price inflation.

For the PVLCC calculations were adopted annual values for the real discount rate of 7.34% and an energy price inflation rate of 7.00%, resulting in a nominal discount rate of 14.85%, obtained through the Equation 5. The time frame for the life cycle was 20 years.

3. Case Study

3.1. Building Model

A building model with 7 floors with 2,520m^2 divided into 42 units (6 units per floor, 2 x 40m^2, 4 x 70m^2) and to attend the cooling demand an Air-Cooled Chiller System and a Thermal Energy Storage (TES) were configured.

The weather input data from Rio de Janeiro, Brazil, were used for the simulations, however initial simulations with hourly data from two other cities in different locations were used to detect the effects of the location in the building cooling demand and the accuracy and reliability of the model. The need for shifting the building cooling demand necessary to attend the comfort levels and the optimization scenarios to avoid the most expensive tariff periods are evident when overlaying this information, as shown in Figure 33.

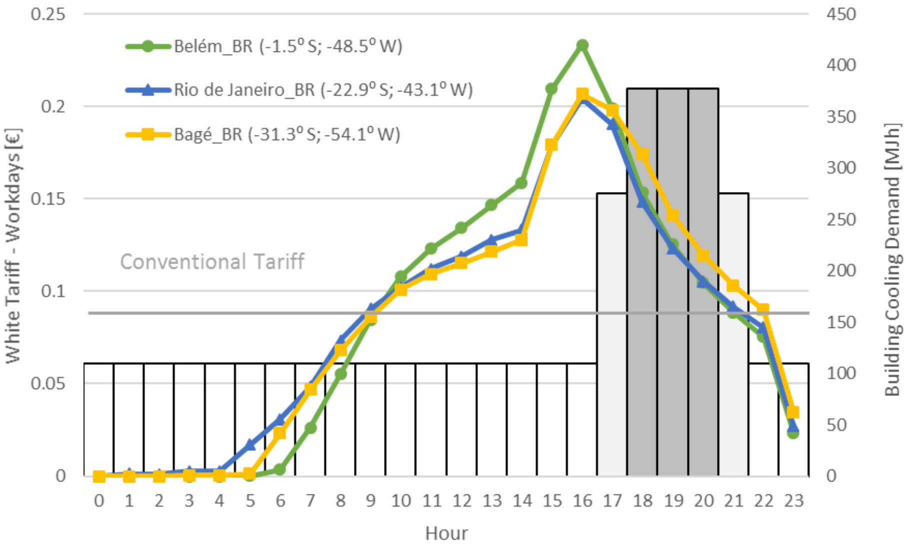


Figure 33 - Building daily cooling energy demand [MJh]; Energy Tariffs [€/kWh]

3.2. Electricity Cost

The electricity tariffs were mainly based on the White Tariff, implemented in Brazil after 2018 (Brazilian National Electrical Energy Agency 2017). The energy and power values for workdays and weekends are shown in Table 5.

Table 5 - White (W) and Conventional (C) Tariffs – Energy [€/kWh]

Tariff types	**Period [h]**		**Price**	
White / Conventional	**Workday**	**Weekend**	**Energy [€/kWh]**	**Power* [€/kW]**
W - P1 - Peak	18-20	-	0.209	7.810
W - P2 – Mid Peak	16-17 / 20-21	-	0.152	4.147
W - P3 – Off Peak	0-16 / 22-24	0-24	0.061	4.147
C - Conventional	0-24	0-24	0.087	5.924

** Typical power price in Brazil, adapted from Blue Tariffs for calculations purpose only.*

3.3. Cooling Demand Profile

The building model was configured with occupation, lightning and equipment loads, as shown in Figure 34, and adjusted with air conditioning information to attend comfort levels according to the Basic Document for Energy Saving (Spain 2013).

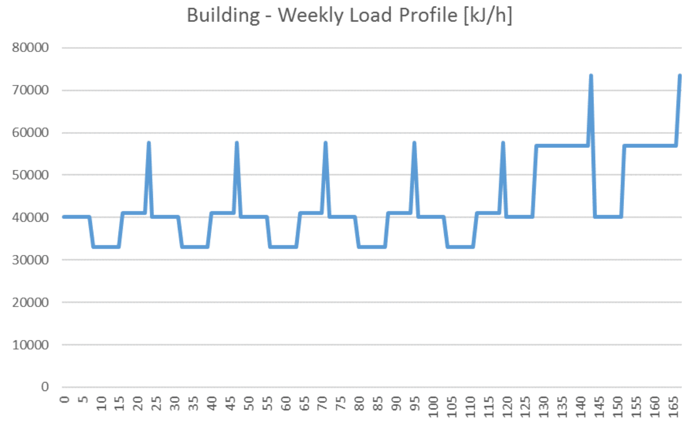


Figure 34 - Building Weekly Load Profile [kJ/h]

3.4. Overview of the Cooling System

A Model were built in the TRNSYS Simulation Studio to simulate the Air-Cooled Chiller and the TES simulations are described below, for each of four the Operation Modes, according to the specifications of ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers. A single model allowed to perform in TRNSYS and GenOpt, the optimizations, considering the Operation Mode itself as a variable to be tested. The control signals are described according to the loop they belong, even in the Operation Mode 1, were the loops are directly connected.

The main items of the cooling system included in the Model are shown in Figure 35 and described below:

Loop 1

- Air-Cooled Chiller (Condenser, Evaporator and Cooling Fans)
- Variable Speed Pump (Chilled water)
- Thermal Energy Storage – TES_IN_1 and TES_OUT_1

Loop 2

- Thermal Energy Storage – TES_IN_2 and TES_OUT_2
- Variable Speed Pump (Chilled water)
- Building Air Handling Unit (AHU) and Fan Coil Unit (FCU)

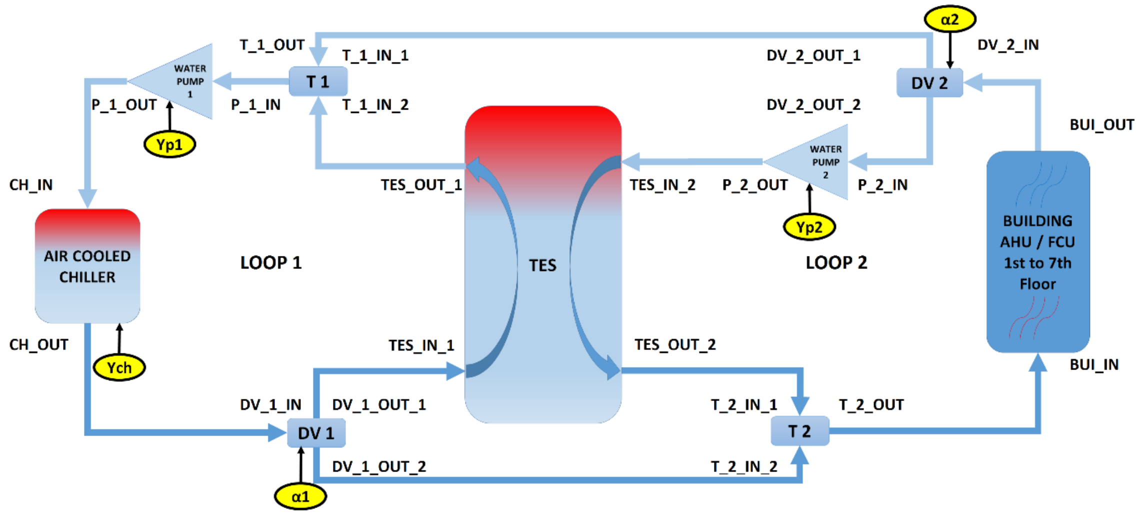


Figure 35 – Air-Cooled Chiller, TES and Building Air Handling Units (AHU)

The Condenser is commonly located on the roof and exchanges the heating from the building using ambient air circulating forced by fans through its coils integrated to the Evaporator that uses a normal water closed loop as refrigerant distributed to the AHU/FCU. Pumps, Evaporator and TES can be located on the roof or inside the building. The system performance depends mainly on the energy losses from the chilled water closed loop used for transferring the cooling energy and the sensible dry bulb outdoor temperature. If the temperature increases the building load increases and the chiller performance decreases, temperature decreases the building load decreases and the chiller performance increases and for this reason, the operation of the Chiller in the Scenarios with TES has a better performance during the nights.

- Loop 1: the chiller and pump works based on signals (time schedule and the TES top temperature);
- Loop 2: the pump works based on the signal (the required water amount for building load demand).

The water pumps operation signal, changes the water flow rate to deliver the amount required to supply the cooling demand, using Equations 1 and 2 for the signal value which is between (0 to stop the pump, up to 1 for 100% of the pump capacity). The TES volume defines the stored energy from the hourly cooling load calculation and can be obtained from the Equations 1 and 3. To start the simulations was considered ΔT of 5 ºC.

All the cooling energy calculations, described on the following equations, were based on the water mass in an hourly base, as shown in Equation (1). The adopted simulation time step of one hour and the characteristics of water, that has a density of 1,000 [kg/m^3], allow to easily obtain from the water mass flow rate [m^3/h] the water mass [kg], multiplying by 1,000, as show at Equation (2).

$$Q = m.Cp.\Delta T \quad or \quad m = \frac{Q}{C_p.\Delta T} \qquad (1)$$

$$Q = Fr.\rho.t.Cp.\Delta T \quad or \quad Q = 1{,}000.Fr.Cp.\Delta T \ \ (t=1\ hour) \qquad (2)$$

Where:

Q = Cooling Load [kWh];

Cp = Specific heat for water 1.163 x 10^{-3} [kWh/kgºC];

m = Water mass [kg];

Fr = Water flow rate [m^3/h];

ρ = Water density, 1,000 [kg/m^3];

t = Time step for simulations, 1 [hour].

The cooling system without TES, (see Figure 36), consists of one pump to circulate the cooled water between the chiller and cooling coil, and the system works based on the load demand signals.

Operation Mode 1 – Chiller only (Base Case)

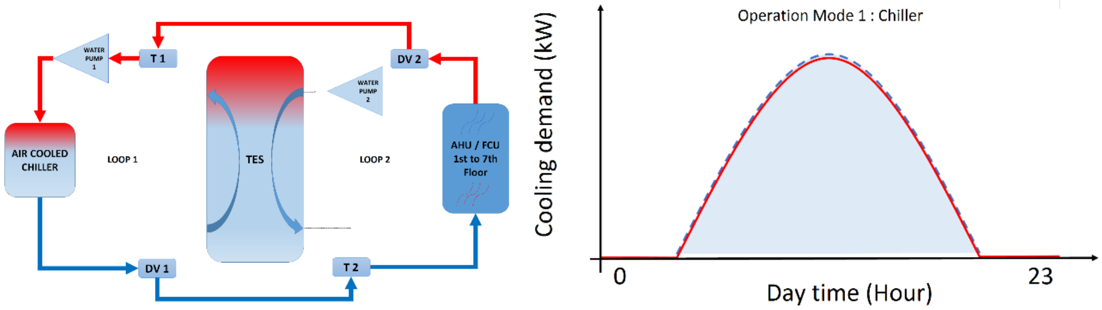


Figure 36 - Chiller only – No TES - Operation Mode 1

In this Operation Mode, Loop 1 and Loop 2 are connected and the TES is out of operation. For energy consuming comparison purposes this configuration is the Base Case.

The control signal for water pump 1 is obtained from Equation (3).

$$Y_{p1} = \frac{m_1}{m_{max}} = \frac{m_2}{m_{max}} = \frac{m}{m_{max}} = \frac{B_{CD}}{C_p.\Delta T} \cdot \frac{1}{m_{max}} \qquad (3)$$

Where:

B_{CD} = building cooling demand [kWh]

$m_2 = m_1 = m =$ water mass necessary to supply the Building Cooling Demand [kg]

m_{max} = Pump capacity [kg/h] or [m^3/h];

Q = Cooling Load [kWh];

Cp = Specific heat for water 1.163 x 10^{-3} [kWh/kg^{o}C];

ΔT = Cool Coil temperature difference $(T_{out} - T_{in})$ [^{o}C];

From the Equation (1), considering Q as hottest hour B_{CD} of the hottest day, represented as B_{CDHH}, detailed in Equation (4), can be determined the most adequate Chiller Capacity necessary to supply the building cooling demand, and this value can be used to validate the theoretical formula for the Chiller sizing, based on building and climate parameters (e.g. USA DOE Chiller sizing guidelines (Burdick 2011)). The Equation (4) also allow to determine the Pump Capacity

m_{max}, that is, m_{HH} in [kg]. The m_{max} divided by the water density (ρ), result the Pump Capacity in [m^3/h], as described in Equation (5).

$$Q = m.Cp.\Delta T \quad \textit{(Hottest hour) or } B_{CDHH} = m_{HH}.C_p.\Delta T \qquad (4)$$

$$m_{max} = m_{HH} = \frac{B_{CDHH}}{C_p.\Delta T} \qquad or \qquad F_{rMax} = \frac{m_{max}}{\rho} \qquad (5)$$

Chiller and Water Pump 1 dimension via partial TRNSYS simulation results.

From the TRNSYS Building Model (Type 56b) simulations, considering the climate data from Rio de Janeiro, Brazil, and the typical loads for lightning, equipment and occupation, the maximum hourly cooling demand load was, $B_{CDHH} = 398{,}211.99$ [kJ/h] or 110.61 [kW] or 31.45 [ton]. These results obtained from the TRNSYS Building Model represents the cooling capacity of the Chiller for the Operation Mode 1, that is, with no TES.

Considering $\Delta T = 5\ [°C]$ and using Equation (5) can be obtained the maximum chilled water mass (m_{max}) or the volume (F_{rMax}) to be pumped from Chiller to the Building Cool Coil in order to supply the Air Handling Units/Fan Coil Units.

$$m_{max} = \frac{B_{CDHH}}{C_p.\Delta T} = \frac{110.61}{1.163x10^{-3}.\ 5} = 19{,}022.25 \left[\frac{kg}{h}\right] \text{ or } F_{rMax} = \frac{19{,}022.25}{1{,}000} = 19.02\ [\frac{m^3}{h}]$$

Using an Industry standard sizing, rule of thumb (Burdick 2011) in Equation , it is possible to verify how the modelling and simulation allow to obtain most accuracy on the sizing of equipment.

$$400\,\frac{ft^2}{ton} = 37\,\frac{m^2}{ton}$$

Building cooled area, 2,520 [m^2] or 27,125 [ft^2], result in a Chiller of about 67.81 [ton]. Most of the double of that calculated through the TRNSYS model.

Operation Mode 2 – Chiller + TES Full Storage

At the cooling system with TES (see Figure 37, Figure 38 and Figure 39), the loop is divided in two loops, one between TES and chiller for charging the TES with cooling energy by decreasing its temperature, and other between the TES and cooling coil to supply the load demand (the heat will be exchanged by the air from the load to decrease the air temperature and increase the cooling water temperature to move back to the TES).

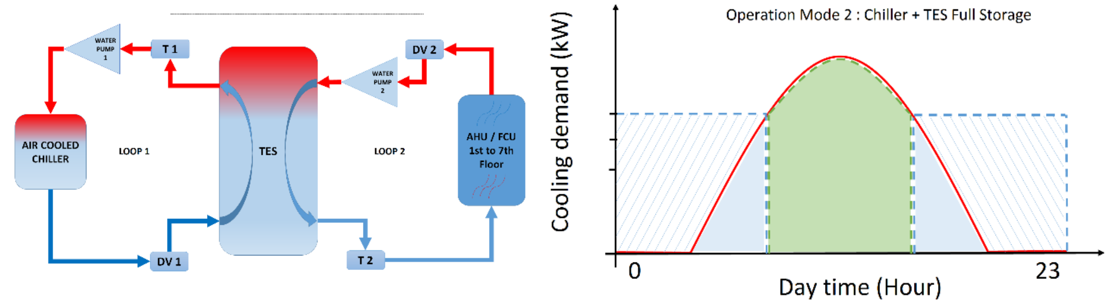


Figure 37 - Chiller + TES Full Storage - Operation Mode 2

$$V = \frac{m_{max}}{\rho}$$

Where:

m_1 = Total water flow rate at LOOP 1 [m^3/h];

m_{T1}= Water flow rate through TES via DV1 at LOOP 1 [m^3/h];

m_{T2}= Water flow rate through TES at LOOP 2 [m^3/h];

Ch_{cap} = Chilller capacity [kW]

Q = Cooling Load supplied by the Chiller to the TES and/or Cooling Coil [kJ/h];

y_{p1} = Signal control value of Water Pump 1 at LOOP 1 [$0 <= y_{p1} <= 1$];

Fr_{max}= Pump flow rate capacity [m^3/h];

ρ = Water density 1000 [kg/m^3];

V = TES volume [m^3]

Operation Mode 3 - Chiller + TES Partial Storage (Load Levelling)

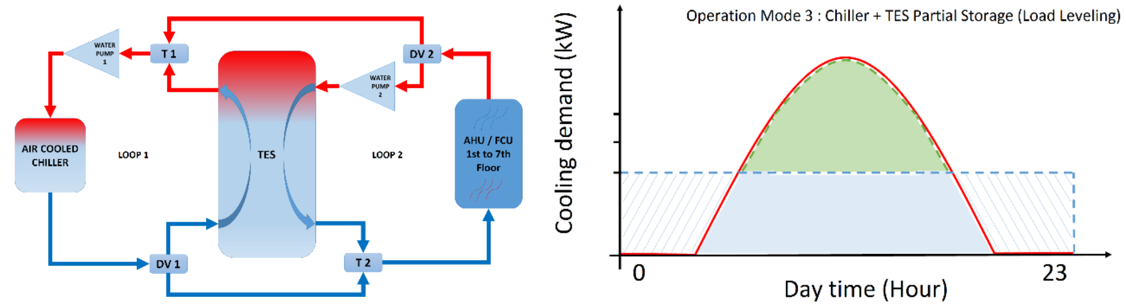


Figure 38 - Chiller + TES Partial Storage (Load Levelling) - Operation Mode 3

Operation Mode 4 - Chiller + TES Partial Storage (Demand Limit)

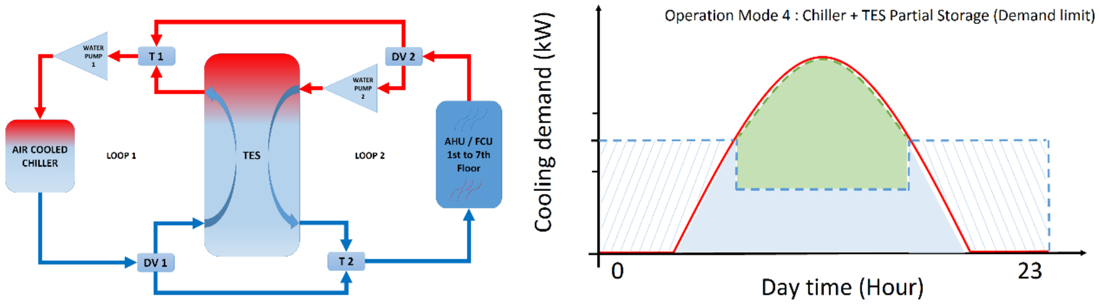


Figure 39 - Chiller + TES Partial Storage (Demand Limit) – Operation Mode 4

The main variables handled to improve the simulation scenarios and to achieve the goals were:

- Chiller capacity and operation schedule;
- TES volume and height;
- Chiller and TES initial cost and operation cost.

The selected Chiller models for the simulations were the York YACL0043 for the Base Case and YACL0022 for the other scenarios. The partial load rates are detailed in Table 2.

Table 6 - Chillers Partial Load Data (York, n.d.)

% Load	**Cooling Capacity [ton]**	**Compressor Input Power [kW]**	**Ambient Temperature [°C]**	**Energy Efficiency Rate EER**
Chiller YACL0043 31.2 Ton (110 kW) – Base Case and Scenario 1				
100	31.2	31.7	35.0	10.7
75	25.1	19.5	28.5	13.2
50	17.6	10.7	20.4	17.1
25	9.7	4.6	12.8	21.5
Chiller YACL0022 15.6 Ton (56 kW) – Scenarios 2, 3, 4				
100	15.6	17.6	35.0	10.3
50	9.7	5.6	20.4	18.8

1 [ton] = 12,000 [Btu/h] = 3.517 [kW] = 12,660.67 [kJ/h]

The Chiller price considered was based on market parameter value of 560.00 [€/ton] and the TES price of 100.00 [€/m^3]. The annual maintenance costs for TES alone are minimal, thus it was considered the annual maintenance costs for the whole refrigeration system of 8.80 [€/ton] (Rismanchi et al. 2012).

3.5. TRNSYS18 Simulations – Base Case and Scenarios

For the Base Case, the cooling load for the building is supplied by a Chiller of 31.2 [ton]. In the Scenario 1, is added a TES (Solico Tanks 2016) with a storage tank capacity of 100 [m^3] to feed the cooling load for the building during the day. The Chiller of 31.2 [ton] operates during the night with the full capacity ratio and charges the TES that delivers the cooling to the building, as shown in Figure 40.

Based on the results of Scenario 1 the Scenarios 2 and 3 were optimized and configured with a smaller TES of 27.7 [m^3] and a Chiller of 15.6 [ton]. The Chiller operates up to 24-hours-a-day with the capacity ratio limited to 35% of maximum cooling load and charges the TES that delivers the cooling to the building. When demand is lower than the 35%, the surplus energy will be stored on the TES and when demand exceeds the limits the TES supplies the excess cooling demand, as shown in Figure 40.

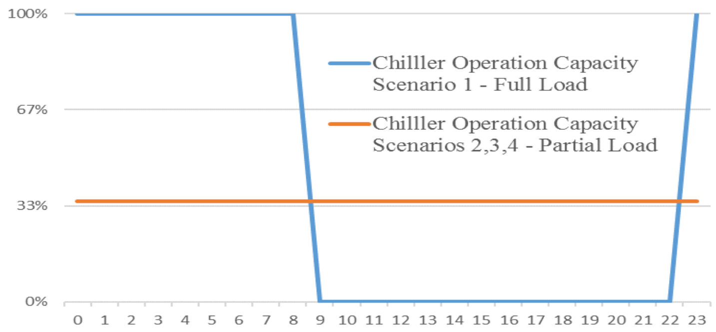


Figure 40 - Daily Chiller Operation Capacity for Base Case and Simulation Scenarios [%]

4. Results and Discussion

4.1. Base Case - GRID + Chiller

The Base Case was configured with the Chiller of 31.2 [ton] dimensioned to attend the cooling demand of the whole building, located in Rio de Janeiro, Brazil. The simulations with Variable Tariffs resulted in more expenses compared to the initial simulations with Conventional Tariffs, evidencing the need for a detailed analysis by the customers, before to contract these tariffs. The energy consumption concentrated on the most expensive period driven by the building cooling demand and the demanded power levels of operation, justified these results, as shown in Figure 41, the day with the highest cooling demand.

Compared to the other building electrical loads, detailed at Table 3, the Chiller was responsible 36% of the building energy consumption and for almost 80% of the electrical power demand, which would represent the main load for the electrical circuits dimensioning. However, even this initial central cooling configuration of 31.2 [ton] and an initial investment of 17,500 [€], if compared to conventional distributed cooling solutions is most economic. In few numbers, the 42 units would demand about 70 individual equipment of 1 [ton], 70 [ton], that would cost about 31,500 [€], based on a market parameter value of 450.00 [€/ton]. Not mentioning the lower Coefficient of Performance, the higher energy demand, power capacity, environmental impact and maintenance costs.

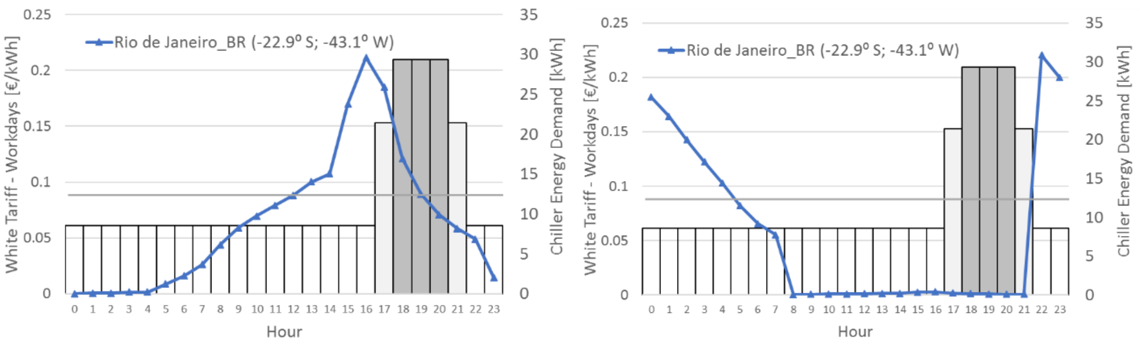


Figure 41 - (a) Base Case – Chiller; (b) Scenario 1 – Chiller Full Load + TES

4.2. Scenario 1 – GRID + Chiller + TES (Full Storage Load)

The simulation results of Base Case allowed the dimension and configuration on TRNSYS18 of a TES of 100 [m^3], with the Chiller of 31.2 [ton] working in its full load, as shown at Figure x, necessary to completely shift the cooling demand from the peak tariffs. The results are shown in Figure 8b. In this configuration, the energy consumption, as detailed in Table 3, was responsible for 40.2% of the building energy consumption and 70% of the electrical power demand. This scenario represented annual energy savings of 7.6% when operating in a variable tariff context, but the elevated power capacity and the LCC analysis (Figure 11), revealed that more improvements could be done.

4.3. Scenario 2 – GRID + Chiller + TES (Partial Load)

The analysis of Scenario 1 allowed to verify that the energy consumption should be distributed from the P3 period to the P1 and P2, in the same proportion of their relative annual number of hours, that is, P1=9%, P2=6% and P3=85% to achieve a smooth distribution of the energy necessary attending the cooling demand with less power capacity.

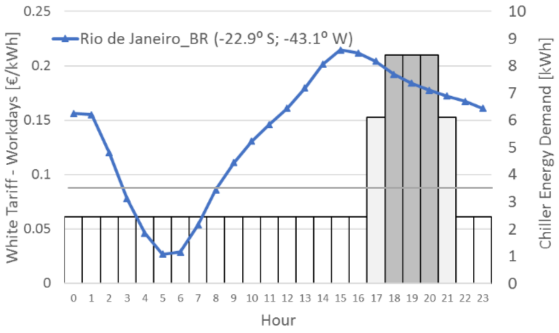


Figure 42 - Scenario 2 – Chiller Partial Load TES

The annual energy consumption obtained at Scenario 1, of 40,279 [kWh], if distributed across the 8,760 [h] of the year, would result in an ideal minimum electrical power of 4.6 [kW], rounded to 5 [kW]. This 5 [kW] was supposed to be the most appropriate power consumption of a Chiller operating during the P1 and P2 and was taken as the prerequisite to choosing a smaller Chiller. By this was, considering a typical COP of 10, a Chiller about 50 [kW] was found in Manufacturer's Manual (York, n.d.), most precisely the Chiller of 15.6 [ton] or 56 [kW]. The power to supply the cooling demand for the TES and the building could be greater than this 5 [kW] but was be configured to the P3 period. For this new scenario, from the Equation 1, also a smaller TES volume was calculated, 27.7 [m^3].

Table 3 shows the results of these simulations related to the energy and power demands. At Scenario 2, the Chiller power reached 14 [kW], as shown in Figure 9 and after some adjusting, the Scenario 3 reached 8 [kW].

4.4. Scenario 3 – GRID + Chiller + TES (Partial Load)

After the simulations of Scenario 2, the Chiller operation was reduced at P2 and P3 periods, as shown in Figure 42, and the Scenario 3 results were adopted as the most feasible to attend the building cooling demand with 8.5% of energy savings and low PVLCC (see Figure 43*Figure 43 - Scenario 3 – Chiller Partial Load TES*).

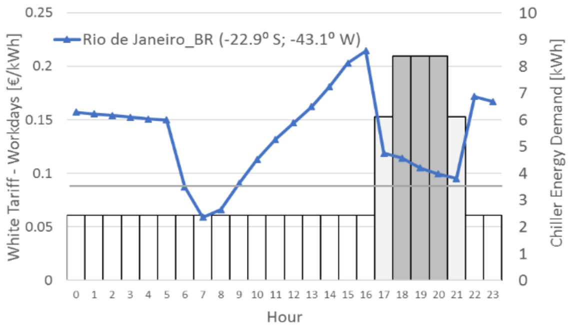


Figure 43 - Scenario 3 – Chiller Partial Load TES

4.4.1. Annual Energy and cost savings

The implementation of TES associated with Chiller, brought savings of about 8.5% in the annual energy cost, as showed in Table 7, Scenario 3.

Table 7 - Building Cooling System Scenarios

	Tariffs		Energy demand [kWh]				Power demand [kW]			Annual Cost [€]	
	Var / Conv	Hours	% Cool	Cooling	Light/ Equip	Total Energy	Cooling	Light/ Equip	Total Power	Var / Conv	Annual Saving
Base Case	P1	780	4.8	4,525	6,376	10,901	14	8	23	8,579.75	- 2.1 %
	P2	520	3.8	3,598	4,251	7,849	22	8	30		
	P3	7,460	27.7	25,837	49,048	74,885	30	14	38		
	C	**8,760**	**36.3**	**33,961**	**59,675**	**93,636**	**30**	**14**	**38**	**8,404.81**	**0.0 %**
1	P1	780	0.1	74	6,376	6,451	0.3	8	9	7,766.78	7.6 %
	P2	520	0.1	68	4,251	4,319	0.5	8	9		
	P3	7,460	40.0	40,137	49,048	89,185	31	14	44		
	C	8,760	40.2	40,279	59,675	99,955	31	14	44	8,992.23	-7.0 %
	P1	780	4.8	4,336	6,376	10,712	8	8	16	8,130.31	3.3 %
	P2	520	3.2	2,884	4,251	7,135	8	8	16		

2	P3	7,460	26.6	24,331	49,048	73,379	9	14	20		
	C	8,760	34.6	31,552	59,675	91,227	9	14	20	8,090.21	3.7 %
3	P1	780	2.9	2,588	6,376	8,965	5	8	13	7,693.16	**8.5 %**
	P2	520	1.9	1,747	4,251	5,998	5	8	13		
	P3	7,460	29.4	26,738	49,048	75,786	9	14	20		
	C	8,760	34.2	31,073	59,675	90,748	9	14	20	8,049.29	4.2 %

4.4.2. Life Cycle Costing Analysis

The annual energy savings analysis was improved with the use of PVLCC (Present Value of LCC), to justify an eventual investment in PV panels.

An optimization using the TRNSYS model and the GenOpt, changing the PV sizing and the Set Chiller/TES Operation Modes (ASHRAE) and aiming the minimum PVLCC for a period of 20 year, as objective function, showed that the Operation Mode 3 (Chiller + TES Partial Load, or Load Levelling) using 14 x 7 PV Panels. These results are shown in Figure 44, and represent savings of 14.5%.

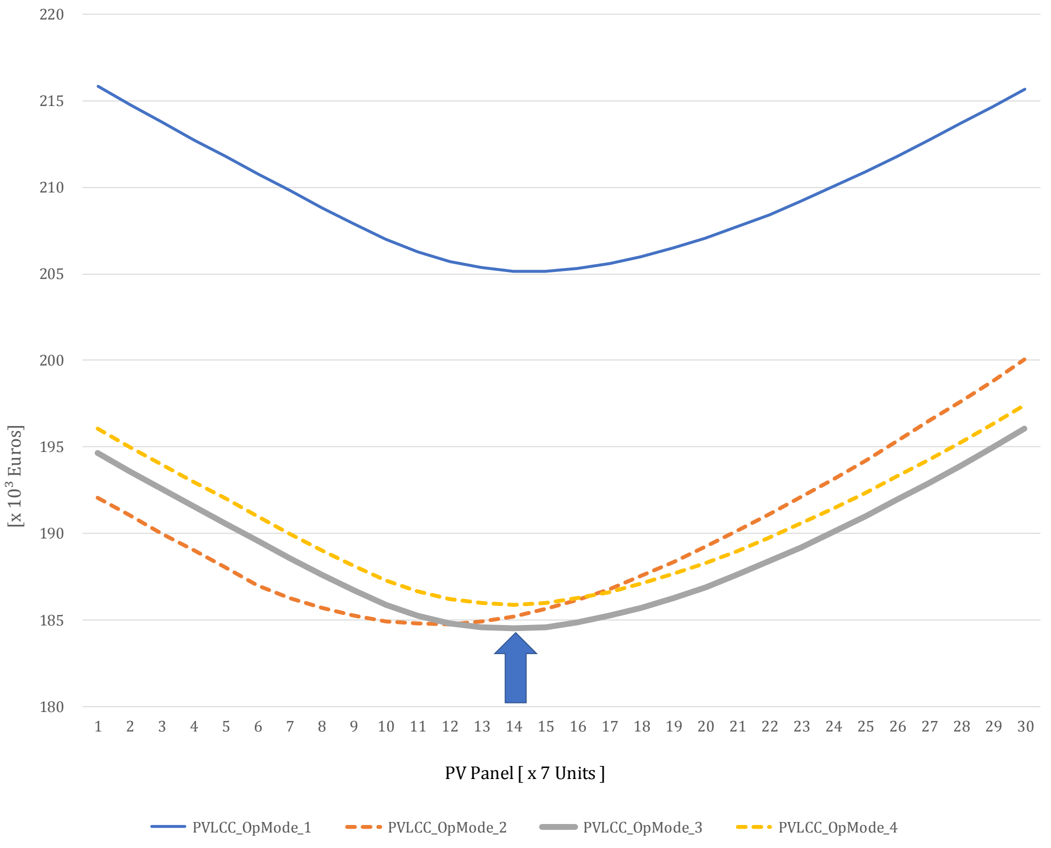


Figure 44 – LCC analysis for each ASHRAE Operation Mode and diverse PV Panels sizing

5. Conclusions

An important issue related to the Energy Efficiency of buildings, that is, the cooling demands and the energy storage were detailed discussed and addressed considering the most recent initiatives related to the Demand Response. The proposed scenario proved that the cooling system, because of its partial load operation, can have the efficiency and lifetime increased when associated with thermal energy storage systems.

The adopted approach, using progressive simulation scenarios has potential to bring most positive results with fewer efforts, once the built model is modular and expansible. The same approach can be adopted for other aspects of the buildings, as lightning, equipment, construction material, alternative energy sources and so on, towards the zero-energy balance in buildings.

The use of TRNSYS 18 Simulation Studio configuring a building with detailed construction characteristics, input data from real equipment and accurate weather information, allowed to reach the initial objectives proposed for these studies and to envisage the applicability of the results in the decision-making process related to the one of the most energy consuming systems of buildings. The optimization process via GenOpt, integrated to TRNSYS 18 allowed to improve the initial results and unveiled the potential of this method, even when the number of alternatives were high, as the PV sizing.

V – General Conclusions

Literature review shows a close relationship between LCC (Life Cycle Costing) and Renewable Energy. Indeed, LCC has been used as a justification for the implementation investments of the last one.

For the Solar Energy solutions, this integration is more evident, mainly because of the relevance of this resource in the renewable energy solutions. The existing gap between the amount of solar energy available on the earth surface and the relative low efficiency of conversion and storage of this energy to attend the demands contributes to this preference, as the LCC can contribute to justify the investments on new solar energy projects and researches.

LCOE (Levelled Cost of Energy) is an important decision-making prerequisite present at the evaluation of different renewable energy solutions. The Literature Review showed that the LCOE depends intrinsically on the LCC calculation. The ancillary solutions related to PV (Photovoltaics), as EES (Electrical Energy Storage) and TES (Thermal Energy Storage) contribute to the improvement of the Capacity Factor of those solutions but represent an increase in their initial investment costs. However, if their implementation costs are considered in a life cycle perspective, their feasibility can be demonstrated.

Considering the above arguments and the others presented in Chapter II - Literature Review, it is reasonable to conclude that the LCC and WLC (Whole Life Costing) is consolidated as one of the most reliable methods to evaluate the viability of renewable energy solutions for buildings and constructed assets, especially those involving solar energy.

The use of Computer Aided Process Engineering tools to configure models of buildings and their facilities allowed to simulate and optimize a variety of configurations of energy solutions, aiming the energy efficiency and autonomy. These detailed models based on TRNSYS Simulation Studio and Energy Plus Weather data represent reliable and reproducible models.

The granularity of the analysed data and the possibility to stablish objective functions based on the Life Cycle Costs showed that the sustainability of the buildings, related to their energy solutions aspects can be demonstrated.

In the Chapter III – Case Study I – Logistics Centre, located in Spain, savings up to 21% on the Life Cycle Costs were obtained. The payback period for the investments was below six years. The electricity consumption could be reduced by 25% by an optimization of the sizing of PV modules.

In the Chapter IV – Case Study II – The Integration of renewable energy and thermal energy storage in residential buildings has been analysed. The case study is in Brazil. The energy consumption due to the use of Chiller/TES could be reduced when associated with a GRID-connected PV System, up to 14.5%, compared to the LCC of a model operation only with the Chiller. It is important to remind that the cooling load for Brazilian residential buildings, represent around 32% of the total building electrical load.

These case study results, obtained with the use of PV and TES associated to Chiller, allow to conclude the potential of the modelling and optimization approach for the energy efficiency of buildings, towards their energy autonomy.

Considering the fact that the heating and lightning loads represents respectively around 34% and 24% of the total building electrical load in countries like Brazil, the use of solar energy, either, thermal or electrical, represent a promising field for future studies, following the same approach.

The portability and modularity of the modelling and optimization methods used in this thesis aim to show the usefulness of these studies to the academic community and other sectors of the construction industry.

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Appendices

Table A 1 - LCC and Solar Energy studies published at 1960's and 1970's

LCC and Solar Energy abstract	**Reference**
Discussed relevant factors limiting the performance of SPV energy converters.	(Wolf 1960)
Summarized the state-of-the-art in SPV energy conversion as applied for space vehicle power supplies. Discuss the silicon solar cell.	(Wolf 1961)
Examined some common design problems of PV irrigation pumps and operational and maintenance requirements.	(McGowen and Burrill 1966)
Compared the results of a systems analysis and economic study of a photochemical solar energy system with a conventional hot-water solar energy system.	(Talbert et al. 1975)
Described a computer program developed for the analyse of a solar heating system for a building considering the yearly costs.	(Fairbanks 1975)
Argued the use of LCC as a methodology for analysing alternative technical proposals based on the first cost, operating cost, maintenance cost, salvage value, and other factors, and presented some drawbacks.	(Hollander 1976)
Reviewed several of basic principles and concepts related to design, implementation, maintenance and utilisation of an extensive database for the facility in nature.	(Williams 1977)
Presented optimal sizing of solar collectors by the method of relative areas, for calculating the approximate collector area, which minimised the total LCC.	(Dennis Barley and Byron Winn 1978)
Developed an economic evaluation and optimisation of a solar heating system, through a procedure for assessing the economic viability regarding the LCC, compared with a conventional heating system.	(Brandemuehl and Beckman 1979)
Performed load optimisation in solar space heating systems. Presented a worth LCC analysis.	(Barley 1979)
Developed an insulation design procedure for solar heating system piping and water-filled thermal storage tanks. Showed the sensitivity of solar systems to cost, in a present-value LCC analysis.	(Jones and Lior 1979)
Outlined US Government LCC contract requirements. Included LCC concepts, LCC program planning, and use of computer aids, data necessary for LCC estimation, and the impact of LCC requirements.	(Schmidt 1979)
The Buildings Owners and Managers Association (USA) described in detail how to implement LCC techniques to provide facilities at the lowest total cost.	(Kirk 1979)

Table A 2 - LCC and Solar Energy studies published at 1980's

LCC and Solar Energy abstract	**Reference**
Compared solar heat pumps system to conventional methods for residential heating, cooling, and water heating. Included LCC analysis to calculate the feasibility.	(Hughes and Morehouse 1980)
Examined the concept of LCC, emphasised the LCC aspect of physical asset management and underlined the values of trade-offs between initial, running, operating and disposal costs.	(Taylor 1981)
Reviewed LCC since its use by the DoD of US. Showed its evolution and the inclusion of facets of system effectiveness in addition to costs.	(Sherif and Kolarik 1981)
Surveyed the publications on LCC, including reliability improvement warranty, and presented an extensive list of references.	(Dhillon 1981)
Presented a systems level approach to reliability analyses for solar PV systems using minimum LCC as the optimisation parameter.	(Stember 1981)
Examined the feasibility of solar assisted heat pump systems for space heating and domestic hot water preheating.	(Chandrashekar et al. 1982)
Focused on reliability and maintainability. Outlined the optimal maintenance schedule to minimise the system´s future total expense maintenance cost.	(Sherif 1982)
Analysed technologies to provide residential space heat and demonstrates the higher LCC efficiency of passive solar heating systems.	(R. A. Bailey 1982)
Presented an LCC methodology for the assessment of process heat generation by solar energy.	(Sherie 1983)
This book presented solar applications in industry and commerce and provided detailed information about the various methods of applying solar energy. Introduced LCC methods for solar systems.	(Meyers 1984)
Exposed a user-oriented algorithm for studying the LCC of production systems under conditions of uncertainty.	(Moore and Ntuen 1984)
Presented an equipment replacement model at a minimum cost, based on the present worth of discounted cash flow.	(Collier and Jacques 1984)
Studied the LCC and annual energy use for a wide range of glazing and sun-control options in high-rise office buildings.	(Winkelmann and Lokmanhekim 1985)
Performed a building energy analysis with a computer program considering hourly heating and cooling loads, simulates the HVAC system.	(Diamond, Hunn, and Cappiello 1985)
Exposed energy conservation measures in the construction of residential houses including insulation material of the walls and roofs to reduce owning and operating costs considering the LCC.	(Fereig and Younis 1985)
Presented the use of LCC application for building energy code compliance.	(Giffin 1985)
Described how the solar cooling system reduces summer utility demand and HVAC system LCC in commercial and institutional.	(Meckler 1986)
Discussed the concept of LCC. Pointed out the problems in the initiation of the process, the planning, realisation, operation and disposal of complex systems.	(Wübbenhorst 1986)
Presented the results of a telephone survey conducted among almost 500 HVAC dealer/contractors to elicit estimates of residential heat pump replacement age and other related issues.	(Lewis 1987)
Presented an approach to estimate the size of heat transfer equipment. Used LCC to select the optimum design.	(Ganapathy 1987)
Explained the use of an analysis procedure developed to determine an equivalent uniform annual cost for alternatives to choose the most cost-effective one. Discussed the LLC used.	(Wipf, Erickson, and Klaiber 1987)
Presented an optimal sizing method for stand-alone PV power (SAPV) systems mathematically formulating the total LCC, developing an algorithm for the solar array and battery capacity.	(Groumpos and Papageorgiou 1987)
Described different methods of analysis of a solar water heating system to determine its economic viability. Discussed the optimum solar collector area based on the life cycle saving and the annualised LCC.	(Hawlader et al. 1987)

Analysed the economic feasibility of the proposal to establish solar power plants in the geostationary orbit.	(Koelle 1988)
Explained how the use of LCC give us a means to find the best retrofit strategy for an apartment block and how important is to consider the entire existing building as an energy system.	(Stig-Inge Gustafsson and Karlsson 1988)
Compared alternatives using case studies of some elements of school buildings. Considers the impact of LCC on the design.	(Ashworth 1989)
Discussed the LCC minimisation considering energy retrofits in multifamily residences. Pointed out the best solution when the LCC for the building is minimal.	(Stig-Inge Gustafsson and Karlsson 1989)
Presented a design for an additional solar dynamic power module for operating on orbit as a power source on the space station Freedom. Showed LCC savings.	(Secunde, Labus, and Lovely 1989)

Table A 3 - LCC and Solar Energy studies published at 1990's

LCC and Solar Energy abstract	Reference
Analysed potentials for tracking PV systems in moderate climates, applying an LCC analysis relative to the costs for a fixed array.	(Nann 1990)
Analysed, based on the LCC method, the economic feasibility of a solar-powered heating/cooling system for a swimming pool/space combination for an aquatic centre in a tropical environment.	(Alkhamis and Sherif 1990)
Discussed the uncertainty and indeterminacy in assessing the economic feasibility of energy options while comparing solar energy and grid electricity for domestic water heating in Brazil.	(Walley, Menezes, and De Souza 1990)
Presented a technique for performing LCC analysis based on a graph-theoretic representation.	(Riggs and Jones 1990)
Presented ten steps to perform a successful LCC analysis, among them, determine purpose, define the system, gather data and perform sanity, sensitivity analysis and risk assessment and establish a baseline.	(Greene and Shaw 1990)
Studied a passive solar heating system for the perimeter zone of office buildings to work during the less busy hours.	(Gutherz and Schiler 1991)
Developed the viability of heat pumps for the heating of swimming pools in South Africa. Calculated and compared the LCC.	(Greyvenstein and Meyer 1991)
Analysed buildings window retrofits considering the interaction between different types of building energy retrofits and LCC.	(S.-I. I. Gustafsson and Karlsson 1991)
Described the contents of four databases developed by the US Army Construction Engineering Research Laboratory for determining LCC of buildings facilities by functional use.	(Neely and Neathammer 1991)
Discussed specific LCC milestones and activities, which program managers could address to apply LCC management techniques to their programs in an efficient way.	(Greene 1991)
Presented the design optimisations of a vapour transport solar water heater to maximise thermal performance and minimise LCC.	(Davidson and Walker 1992)
Evaluated the performance of space solar Brayton cycle power systems. Examined the effects of pressure ratio, recuperation effectiveness, and compressor inlet temperature on LCC.	(Diao 1992)
Described two models, the LCC and the COO (cost of ownership), and their use as an aid in meeting the objective of creating products that have the lowest LCC for both the manufacturer and the customer.	(Carrubba 1992)
Presented a new method of project LCC analysis that uses a simulation technique and a computer simulation. After applying in several projects points out that, the main risk is in the discount rates.	(Zhi 1993)
Analysed the impact of Stirling engine operational requirements on a dish Stirling system LCC. Presented the results of analyses that define the performance required to meet desired utility-levelled energy cost goals.	(Stone, Drubka, and Braun 1994)
Demonstrated benefits of the interaction between the design and engineering stage, and field service support. Presented a model, which estimates discounted and undiscounted LCC of a durable product.	(Hegde 1994)
Described how manufacturing firms could develop a Design for Environment toolkit, including performance assessment capabilities for analysis of design trade-offs.	(Fiksel and Wapman 1994)
Showed that LCC analysis includes all cost factors (fixed and variables) of a product manufacturing processes and can aware buyers of all possible costs, before purchasing.	(Vivona 1994)
Performed a case study of solar domestic hot water heating in Ontario. Presented results of LCC analyses for installing a typical solar system in single-family dwellings.	(Berbash, Chandrashekar, and Calamai 1995)
Analysed and identified the issues and provided a framework for design and implementation of an LCC management system.	(Ahmed 1995)

Presented an application case study and comparison of performance results between two computational models for simulating the performance of hybrid wind/PV/diesel power systems.	(McGowan et al. 1996)
Described the design, development and field tests of a solar grain dryer incorporating PV powered air circulation.	(Mumba 1996)
Studied the durability of solar reflector materials exposed to environmental stresses.	(Jorgensen, Kim, and Wendelin 1996)
Presented an economic analysis of solar energy systems using spreadsheets, and an optimisation example for a hot water system.	(S Kalogirou 1996)
Presented a summary of performance and cost evaluation results obtained from a 2-year monitoring period of the first stand-alone PV system in Malta.	(Iskander and Scerri 1996)
Described a survey conducted in 1995 indicating that 40% of municipalities in the US use LCC analysis and some had been used for over 20 years.	(Arditi and Messiha 1996)
Studied the feasibility of a solar-powered heating/cooling system for an aquatic centre in hot and humid climates using two thermal storage tanks for the collector and domestic use.	(Alkhamis and Sherif 1997)
Suggested that project managers should be familiarised with what the LCC approach involves, to understand how they might then contribute to the enhanced quality decision making which it makes possible.	(Woodward 1997)
Provided a systematic, project-based approach based on LCC, minimum performance requirements, and a cost classification scheme that organises a construction material's LCC advantages and disadvantages.	(Ehlen, Mark, and Ehlen 1997)
Looked at the issues of LCC analysis and the tools developed to provide engineers with cost information to guide them in design, mainly in the design for assembly (DFA).	(Asiedu and Gu 1998)
Analysed different strategies to attend the electrical energy demand in villages at minimum cost by utilising bioenergy-based power generation (biomass, biogas) or solar PV.	(Rana et al. 1998)
Performed a financial evaluation of renewable energy technologies options for water pumping in rural areas, including solar PV pumping systems, biogas and windmill pumps.	(Rubab and Kandpal 1998)
Described how to design a Mixed Integer Linear Programming (MILP), a model of a building and how different cost elements of the climate shield influence the optimal solution. Minimization of LCC was a goal.	(Stig-Inge Gustafsson 1998)
Described the development and testing of a novel technique, which reduced the amount of data about running costs of buildings from a set of data for 20 buildings at York University.	(Al-Hajj and Horner 1998)
Studied the feasibility of a solar desiccant air-conditioning system with a transient simulation for thermal and economic LCC analysis.	(Davanagere, Sherif, and Goswami 1999)
Presented a techno-economic analysis of multistage stacked tray solar still coupled with a solar collector. Based the economic analysis on the LCC of the system.	(Adhikari and Kumar 1999)
Developed a systematic approach for optimisation of walls insulation material thickness applied to Palestine. Based the optimisation of the LCC analysis.	(Afif Hasan 1999)

Table A 4 - LCC and Solar Energy studies published at 2000's

LCC and Solar Energy abstract	**Reference**
Presented an economic analysis of PV stand-alone residential households evaluating the cost-effective sizing at various European and Mediterranean locations.	(Lazou and Papatsoris 2000)
Developed a methodology, via simulation calculations, to determine the optimal size of a PV-hybrid power system and stand-alone system management, incorporating battery storage.	(Muselli et al. 2000)
Presented an analytical optimisation of a remote power system for a hypothetical Alaskan village, considering the potential of generating renewable energy (e.g., the wind and solar).	(Isherwood et al. 2000)
Studied the optimisation of collector area in domestic solar water heating systems. Presented a systematic sizing approach for the solar system and applies to a case study, based on the LCC analysis.	(A Hasan 2000)
Evaluated the life-cycle energy, greenhouse gas emissions, and LCC of a contemporary U.S. residential home to study opportunities for conserving energy throughout pre-use, use and demolition phases.	(Keoleian, Blanchard, and Reppe 2000)
Aimed to challenge the traditional way of assessment of the value of green buildings regarding their environmental friendliness, energy efficiency and WLC.	(Bartlett and Howard 2000)
Identified some of the critical gaps between the theory and practice of LCC analysis to discover strategies that encourage greater use.	(Cole and Sterner 2000)
Reported the results of a survey that examined the extent that Swedish client in the building sector uses LCC estimations.	(Sterner 2000)
Studied the prediction and optimisation of LCC in the early design of buildings.	(Bogenstätter 2000)
Explained how to optimise retrofit measures in buildings, i.e. how to act to minimise the LCC of buildings in Sweden.	(Stig-Inge Gustafsson 2000)
Inserted costs in LCA to extend its primary goal of identifying environmental impacts resulting from a product, process or activity.	(Shapiro 2001)
Proposed integration between LCC Analysis and LCA. Stated that the result is an ability to take both economic and environmental performance and their trade-off relationships.	(Norris, Road, and Berwick 2001)
Showed the advantages of adopting the "design for maintenance" approach. Discussed the application of reliability, maintainability and risk analysis tools and methods to minimise LCC of a system.	(Markeset and Kumar 2001)
Demonstrated the software BEES (Building for Environmental and Economic Sustainability).	(Lippiatt and Boyles 2001)
Analysed optimal fenestration retrofits of buildings using mixed integer linear programming (MILP) technique. Simulated the effects of solar radiation in the windows and glass panes in the LCC.	(S.-I. Gustafsson 2001a)
Studied the optimal use of solar collectors for residential buildings considering the storage of the warm water in accumulators-items and the minimum LCC concept as a criterion.	(S.-I. Gustafsson 2001b)
Used the TRNSYS, for the modelling and simulation of the energy flows, to examine measures to reduce the thermal load and to lower building energy consumption and their LCC.	(Florides, Tassou, et al. 2002)
Presented a modelling and warming impact assessment of a domestic-size absorption solar cooling system. Calculated the total LCC of a complete system, for a lifetime of 20 years.	(Florides, Kalogirou, et al. 2002)
Demonstrated a procedure for quantifying the effects of inverter failures (as most dominant) on total lifetime PV system energy production, based on criteria of total lifetime energy output and LCC.	(Pregelj, Begovic, and Rohatgi 2002)
Presented an analysis of the general cost associated with a solar-powered vapour absorption air-conditioning system and a vapour compression system. The selection was based on the minimum LCC.	(Elsafty and Al-Daini 2002)

Evaluated the LCC of several power supply alternatives to some telecommunication systems. Proved that a hybrid (Solar/Generator Set) power supply option shows to be cost-effective.	(Oparaku 2002)
Assessed the viability of hybrid geothermal heat pump (GHP) systems with solar thermal collectors. Used an LCC analysis for 20 years of operation.	(Chiasson and Yavuzturk 2003)
Addressed the technical and economic viability of using a PV system to supplement an existing diesel generator-based supply in a typical secondary school located in East Malaysia.	(Ajan et al. 2003)
Evaluated the use of PV technology for developing remote areas in Egypt, compared to diesel units. Proved that PV-battery systems are most cost-efficient.	(Mahmoud and el Nather 2003)
Simulated an operation strategy of residential centralised PV system in remote areas. Proved that the LCC and the price of kWh generated in a centralised system are lower than an individual one.	(Dakkak et al. 2003)
Analysed the greenhouse emissions of domestic solar hot water systems compared to conventional fossil fuel-powered systems.	(Crawford et al. 2003)
Worked on enhancing the efficiency of solar cells and extending their performance life. Adopted an LCC approach.	(Mansour 2003)
Performed a comparative analysis of three PV street lighting systems installed in Thailand. Stated that the LCC analysis is the appropriate method for comparing the systems.	(Hiranvarodom 2003)
Presented the improvements of insulation in external walls of buildings in the coldest cities of Turkey. Based on the LCC compared energy saving and the applied insulation thickness.	(Çomaklı and Yüksel 2003)
Explained that within the area of product-focused environmental management, lifecycle management (LCM), attempts to put sustainable development into practice.	(Rebitzer and Hunkeler 2003)
Highlighted the economic benefits of green roofs in Singapore. Observed that LCC of extensive green roofs is lower than that of exposed flat roofs, despite its higher initial costs.	(N. H. Wong et al. 2003)
Summarised the studies on space solar power systems of the National Space Development Agency of Japan. Focus on creating an LCC model of the Space Solar Power Systems.	(Mori et al. 2004)
Carried outs the optimisation of a lithium-bromide chiller and an ejector cooling cycle using the LCC savings function as the objective function, expressed regarding the capital and the operating cost.	(Colle and Vidal 2004)
Identified ten LCC-oriented environmental accounting tools suggested as useful in environmental decision-making. Tried to handle LCC inconsistencies due to its oversimplification.	(Gluch and Baumann 2004)
Described a method for a detailed LCA of an individual house in New Zealand based on the embodied, operating energy requirements, and the LCC over its useful life.	(Mithraratne and Vale 2004)
Evaluated energy and cost efficiency of glass facades in high-rise buildings. Proposed a double skin glass facade based on the LCC.	(Cetiner and Özkan 2005)
Analysed the financial incentives for residential owners of a PV system in the US. Assess its impact applied to the PV systems on its LCC of energy generation for homeowners in nine states of the US.	(Bhattacharjee and Duffy 2005)
Proposed a system that allows the description, measurement and assessment of various aspects of building performance. Identified possible sustainability key performance indicators.	(Lützkendorf and Lorenz 2005)
Presented a multi-objective optimisation model to assist designers in green building design. Employed LCA methodology to evaluate design alternatives for both economic and environmental criteria.	(Weimin Wang, Zmeureanu, and Rivard 2005)
Reviewed the literature related to the subject area of the intelligent building. Summarized a few future research directions.	(J. K. W. Wong, Li, and Wang 2005)
Conducted the LCA and LCC analysis for a distributed 2.7 kWp grid-connected mono-crystalline solar PV system, regarding a fuel oil-fired steam turbine and their greenhouse gas emissions.	(Kannan et al. 2006)

Studied the influence of pumping head, insulation and PV array size on PV water pumping system performance. Determines the optimum PV array size considering LCC analyses.	(Odeh, Yohanis, and Norton 2006)
Reviewed the different technological options available for distributed generation and their status. Evaluated them based on the cost of production and potential in India.	(Banerjee 2006)
Performed the design optimisation of PV powered water pumping systems in Kuwait. Implemented the LCC method to evaluate the economic feasibility of the system.	(Ghoneim 2006)
Conducted the applications and analysis of a small wind turbine system in Turkey, based on energy conservation, pollution prevention, resource efficiency, systems integration and LCC.	(Ozgener 2006)
Analysed the economic feasibility of a solar greenhouse integrated solar-assisted geothermal heat pump system in Turkey.	(Ozgener and Hepbasli 2006)
Studied the influence of the charge regulator strategy on the state of charge and lifetime of valve-regulated lead-acid (VRLA) battery in household PV systems.	(Yang et al. 2006)
Analysed and proposed improvements in the buildings insulations in Turkey, based on LCC analysis.	(Bolattürk 2006)
Discussed the optimisation model for community-based hybrid energy system, as a solution for electrification of remote rural areas.	(Ashok 2007)
Proposed a methodology to determine the design space for synthesis, analysis, and optimisation of solar water heating systems. Optimized the system minimising the annual LCC.	(Kulkarni, Kedare, and Bandyopadhyay 2007)
Performed a life cycle energy, emissions and cost inventory of power generation technologies in Singapore. Used LCA to quantify environmental impacts and LCC.	(Kannan et al. 2007)
Presented the development of a computational model, using MATLAB, for optimal sizing of the solar-wind hybrid energy system. Used the LCC for evaluation of different configurations.	(Gupta, Kumar, and Agnihotri 2007)
Performed the sizing optimisation of a hybrid wind/PV system with battery storage.	(Belfkira, Barakat, and Nichita 2008)
Analysed the cost-effectiveness of a standalone small-scale renewable energy-powered seawater reverse osmosis (SWRO) system.	(Gilau and Small 2008)
Performed the LCC analysis of HPVT air collector under different Indian climatic conditions. The focus was to see the effect of interest rate, the life of the HPVT air collector and subsidy aspects.	(Raman and Tiwari 2008)
Presented the integration of environmental and economic performance of processes in a case study of advanced oxidation processes for wastewater treatment.	(Mufioz et al. 2008)
Analysed the performance of a building envelope in Thailand, using hourly average meteorological data for insulations to calculate the solar gain by light transmission.	(Praditsmanont and Chungpaibulpatana 2008)
Developed a methodology based on LCC and sensitivity analysis to determine cost boundaries for new PV solar cell technologies.	(Azzopardi, Mutale, and Kirschen 2008)
Performed the LCC analysis of new fibre reinforced plastic (FRP) based solar parabolic trough collector (PTC) hot water generation system.	(Valan Arasu, Sornakumar, and Arasu 2008)
Analysed data collected from an experimental green roof plot to develop a benefit-cost analysis (BCA) for the life cycle of long (thin layer) green roof systems, in Georgia (US).	(Carter and Keeler 2008)
Assessed the LCC for a single-family detached house by combined simulation and optimisation. Optimized values of five selected design variables in the building construction and HVAC system.	(Ala Hasan, Vuolle, and Sirén 2008)
Analysed energy and cost aspects of semi-transparent PV in office buildings. Studied the thermal and visual properties, energy performance and the financial issue of such solar facades.	(D. H. W. Li et al. 2009)

Presented the LCC analysis of single slope HPVT active solar stills. Compared the payback and the energy payback time (EPBT) of both, passive and active systems.	(S. Kumar and Tiwari 2009)
Presented a methodology for determining the specifications of an isolated renewable energy source (RES) in a Greek island for power production system on an environmentally sensitive ecosystem.	(Katsaprakakis et al. 2009)
Compared various optimisation criteria for a solar domestic hot water system (SDHWS). Considered the energetic, exergetic, environmental (CO2 emissions) and financial LCC analysis.	(Fraisse et al. 2009)
Presented an analysis of carbon credit earned by each district for supplying minimum subsistence electricity to each family in India. Performed the LCC analysis of stand-alone photovoltaic (SAPV).	(Prabhakant and Tiwari 2009)
Proposed that bio-retention, or variations such as bio-infiltration and rain gardens, has become one of the most frequently used storm-water management tools in urbanised watersheds.	(Davis et al. 2009)
Outlined that the thermal insulation is one of the most effective ways of building energy conservation for cooling and heating. Calculated, using the LCC for different materials, savings and payback periods.	(Jinghua Yu et al. 2009)

Table A 5 - LCC and Solar Energy studies published at 2010's

LCC and Solar Energy abstract	**Reference**
Analysed a building integrated PV thermal (BIPVT) system fitted as the rooftop of a building to generate electrical energy higher than that produced by a similar building integrated PV (BIPV) system.	(Agrawal and Tiwari 2010)
Discussed three types of insulation for buildings in Turkey. Carries out an LCC analysis was utilising the present-worth cost method.	(Aktacir, Büyükalaca, and Yılmaz 2010)
Estimated the yearly cooling transmission loads for two types of insulation materials and two typical wall structures. Used loads as inputs to an LCC to determine the optimum insulation thickness.	(Daouas, Hassen, and Aissia 2010)
Explored the LCSA for products and processes. Discussed the use of LCA for the environmental dimension as a well-established tool.	(Finkbeiner et al. 2010)
Discussed the estimation life-cycle energy savings, carbon emission reduction, and cost-effectiveness of energy efficiency measures in new commercial buildings.	(Kneifel 2010)
Developed and applied a simulation tool to optimise building shape and envelope features. Showed that rectangular and trapezoidal shaped buildings have the lowest LCC.	(Tuhus-Dubrow and Krarti 2010)
Discussed the energy savings over a lifetime of 10 years and calculates payback periods for different energy types and insulation materials applied externally on walls, in Turkey.	(Ucar and Balo 2010)
Provided a techno-economic comparison of rural electrification of two options, solar home systems not connected to the electric grid and an off-grid PV plant with their distribution network.	(Chaurey and Kandpal 2010)
Conducted the optimisation and LCC of health clinic PV system for a rural area in Iraq using HOMER software.	(Al-Karaghouli and Kazmerski 2010)
Carried out a feasibility analysis of off-grid stand-alone renewable technology generation system for some remote rural areas in one Sahelian country (Africa).	(Thiam 2010)
Conducted an economic analysis of PV systems for household applications in Turkey.	(Camdali 2010)
Presented PV systems as a competitive cost option to supply energy to off-grid agricultural communities in arid regions of Egypt.	(Qoaider and Steinbrecht 2010)
Assessed the economic feasibility of operational energy reduction options in a house in Malaysia.	(Zaki, Nawawi, and Ahmad 2010)
Designed an energy-efficient stand-alone distributed generation system employing renewable energy sources and smart grid technology for Native American villages in rural Alaska.	(Wies, Johnson, and Aspnes 2010)
Performed an LCC analysis over a building lifetime of 30 years and shows that the south orientation is the most economical with optimised insulation thickness, in Tunisia.	(Daouas 2011)
Explained the development of LCA from the 1980s to LCSA. Pointed out the introduction of LCC models in the 1980s and 1990s.	(Guinée et al. 2011)
Presented the Net Zero Energy House (NZEH) an energy efficient house that uses available solar technologies to generate at least as much primary energy as the house uses over the course of the year.	(Leckner and Zmeureanu 2011)
Applied an integrated thermal modelling to an extensive sample of house designs to investigate LCC in a cold temperate climate in Australia.	(Morrissey and Horne 2011)
Presented the economic assessment of solar electricity production from organic PV modules in a domestic environment. Calculated the LCOE.	(Azzopardi et al. 2011)
Performed the techno-economic analysis of a wind-solar hybrid renewable energy system with rainwater collection feature for urban high-rise application in Malaysia.	(Chong et al. 2011)
Assessed the LCC analysis of a multi-storey residential Net Zero Energy Building (NZEB) in Denmark. Discussed the NZEB cost-effectiveness and feasibility, based on energy saving measures.	(Marszal and Heiselberg 2011)

Examined the technical and economic performance of residential solar rooftop water heating in the US and the influence in the electricity prices.	(Cassard, Denholm, and Ong 2011)
Conducted the viability analysis of solar or wind energy sources for water pumping systems in the Algerian Sahara regions.	(Bouzidi 2011)
Analysed thermal and economic aspects of windows design for different climate zones in Germany, as a critical factor for the effectiveness of the passive solar design.	(Jaber and Ajib 2011)
Studied the optimum insulation thickness of residential roof concerning solar-air degree-hours in hot summer and cold winter zone of China.	(J Yu et al. 2011)
Presented the LCA of a Solar Assist Plug-in Hybrid Electric Tractor (SAPHT) in comparison with a conventional tractor. Analysed the life cycle based on economic cost and environmental emissions.	(Mousazadeh et al. 2011)
Proposed a hybrid solar cooking system using as an energy source a combination of the solar thermal energy and the Liquefied Petroleum Gas (LPG). Discussed the design and LCC of the system.	(Prasanna and Umanand 2011)
Evaluated a Battery Powered Electric Vehicle (BPEV) charged via solar PV arrays developed for light agricultural duties in remote hilly areas in Lebanon.	(Redpath et al. 2011)
Presented the design and analysis of an electromechanical energy storage system to enhance rural electrification in sub-Saharan Africa.	(Okou et al. 2011)
Showed the optimum insulation thicknesses for the different wall types; stone, brick and concrete, very common in building construction in Turkey.	(Bektas Ekici, Aytac Gulten, and Aksoy 2012)
Evaluated economic and environmental effects of functional improvement in elementary school facilities in South Korea by applying various improvement scenarios based on green roofs.	(TaeHoon Hong, Kim, and Koo 2012)
Applied a sequential search technique to optimise the design of residential buildings in Tunisia to minimise their energy LCC while increasing their energy efficiency.	(Ihm and Krarti 2012)
Developed a methodology and an associated LCC calculation platform to identify the economic, efficient design solutions for residential Net Zero Energy Building (NZEB).	(Kapsalaki, Leal, and Santamouris 2012)
Evaluated savings of ten-selected building thermal insulation materials on the energy consumption of air-conditioning for cooling based on tropical climate condition in Malaysia.	(Mahlia et al. 2012)
Discussed the on-site and off-site energy supply for Net Zero Energy Buildings (NZEB) in Denmark. Deployed the LCC analysis.	(Marszal et al. 2012b)
Investigated optimum thickness of thermal insulation used to reduce heat gain and losses in buildings under dynamic thermal conditions by using the climatic conditions in Turkey.	(Ozel 2012)
Discussed the global market potential for solar thermal, PV and combined PVT technologies. Identified new research topics and directions to improve the performance of the PVT.	(Zhang et al. 2012)
Performed LCC and LCA of solar water heating systems (SWHS) in the US.	(Hang, Qu, and Zhao 2012)
Conducted the environmental impact assessment of a solar water heating system (SWHS) in Greece, using LCA.	(Koroneos and Nanaki 2012)
Developed a mathematical closed-form expression for the evaluation, in the period 2010-2050, of the LCOE of a CSP plant.	(Hernández-Moro and Martínez-Duart 2012)
Studied the effects of window alternatives on energy efficiency and building economy in high-rise residential buildings in Turkey.	(Yaşar and Kalfa 2012)
Conducted a techno-economic evaluation of solar-wind hybrid power system in Turkey. Analysed six different scenarios using LCC in the viewpoint of technical and economic aspects of the system.	(Ozgur 2012)
Emphasized the pumping water need all around the world and analyses standalone PV technologies, mainly in irrigation systems, focused on Turkey scenario.	(Senol 2012)

Presented an approach for the optimisation of PV-Wind hybrid systems with battery back. Provided the LCC with payback time and LCOE with Net Metering as part of the economic analysis.	(Shadmand and Balog 2012)
Conducted an LCC analysis of standalone PV-diesel system versus PV-H2 system. Pointed out that hydrogen as a long-term storage medium in PV systems has been a subject of interest in recent years.	(Raj and Ghosh 2012)
Discussed cost-optimal solutions for the nZEB. Compared combinations of energy-saving measures (ESM) and energy supply systems including renewable energy sources (RES).	(Hamdy, Hasan, and Siren 2013)
Illustrated the modelling and simulation of hybrid energy systems (HES), and multi-objective optimisation carried out to support decision-making.	(Perera et al. 2013)
Discussed that LCA, LCC and social LCA (sLCA) already attempt to cover sustainability pillars, despite different levels of methodological development.	(Sala, Farioli, and Zamagni 2013)
Analysed the feasibility of combined solar thermal and ground source heat pump system in cold climate in Canada. Examined with TRNSYS simulation tool the viability GSHP.	(Rad, Fung, and Leong 2013)
Studied the organic PV for mobile applications. Evaluated the roll-to-roll processed indium and silver free polymer solar cells through analysis of LCC.	(Espinosa et al. 2013)
Presented a framework for the implementation of a new renewable energy system (NRES) in an educational facility.	(Taehoon Hong, Koo, and Kwak 2013)
Verified the optimal design of hybrid renewable energy systems (HRES) using hydrogen storage technology for data centre applications.	(Iverson et al. 2013)
Studied the performance and LCC analysis of PCM in TES, with different melting temperatures in heating systems.	(Rezaei et al. 2013)
Performed the LCC analysis of pump as turbine (PAT) for hydropower plants, integrated with solar PV, in India.	(Motwani, Jain, and Patel 2013)
Calculated the LCC of 12 energy management systems for a hospital facility and compare the prices of renewable and traditional energy management solutions, in the Finnish energy market.	(Kantola and Saari 2013)
Presented the LCC analysis of a sustainable solar water distillation technique.	(Ahsan et al. 2013)
Performed the study of a hybrid renewable energy system combining the generation of power through solar, wind and biomass systems to meet the demand of rural electrification in India.	(Dhass and Harikrishnan 2013)
Summarized and organised the literature on LCA, life cycle energy analysis (LCEA) and LCC related industry and building sector.	(Cabeza et al. 2014)
Modelled a membrane liquid desiccant air conditioning (M-LDAC) system using the TRNSYS building energy simulation software.	(Abdel-Salam and Simonson 2014)
Studied the integration of single polyethene heat exchanger loop underneath PV modules, designed to act as a roof element. Carried out a techno-economic analysis by applying LCC.	(Buker, Mempouo, and Riffat 2014)
Compared the economic aspects of white, green, and black flat roofs in the USA and presents an economic perspective on roof colour choice using a 50-year LCC analysis.	(Sproul et al. 2014)
Studied the optimal sizing, operating strategy and operational experience of a standalone microgrid in China.	(Zhao et al. 2014)
Performed the sustainability assessment of energy systems scenarios in Mexico, integrating environmental, economic and social aspects.	(Santoyo-Castelazo and Azapagic 2014)
Developed a long-term thermal and LCC analysis of the energy conservation potential and viability of direct expansion solar-assisted heat pump for low-temperature water heating applications.	(Chaturvedi, Gagrani, and Abdel-Salam 2014)
Modelled and analysed hybrid energy systems compound by different energy sources (solar, wind, hydro, diesel generator) as well as energy storages interconnected to meet the load energy demand.	(Kusakana and Vermaak 2014)
Performed the optimisation of a residential solar system for minimum LCC, energy use and exergy destroyed in Canada.	(Cheng Hin and Zmeureanu 2014)

Developed a framework to highlight and quantify the tradeoffs between rooftop and ground-mounted PV systems in the US. Used LCC and life cycle land use footprints.	(Lakhani, Doluweera, and Bergerson 2014)
Modelled the effect of inter-cooling on the performance and economics of solar energy assisted hybrid air conditioning system. Investigated also the LCC.	(Elzahzby et al. 2014)
Performed LCC analysis of passive house prototype in Romania. Created a mathematical model based on a passive house, including its technical design variations.	(Badea et al. 2014)
Developed a framework to compare energy and transportation technologies regarding cost-efficient greenhouse gas emission reduction in Belgium.	(De Schepper et al. 2014)
Presented a study of an off-grid PV system for electrification of a single residential household in Pakistan.	(Ghafoor and Munir 2015)
Examined the existing literature in the analysis of LCC of electricity storage systems, providing an updated database for the cost elements Analyses LCC and LCOE.	(Zakeri and Syri 2015)
Explained that the election of the best alternative for building rehabilitation should involve LCC analysis. Proposed Monte Carlo simulation to calculate statistical distributions of energy demand.	(Almeida, Ramos, and Manuel 2015)
Employed LCA to compare the effects of three different shading materials (wood, aluminium and PVC) on building energy consumption and their impacts on the environment.	(Babaizadeh et al. 2015)
Performed the optimal sizing and tilting of a hybrid PV / battery/diesel generator system for the remote locations in India, using artificial intelligence techniques.	(S Berclin Jeyaprabha and Selvakumar 2015)
Developed a multi-objective optimisation model for establishing a low-carbon scenario to achieve the national carbon emissions reduction target for the South Korean residential building sector.	(Choongwan Koo et al. 2015)
Developed a program-level management system for the LCA and LCC assessment of complex building projects.	(Kim et al. 2015)
Developed an optimisation model to determine the best size of a stand-alone hybrid renewable energy system for electrification of a remote area in Iran.	(Askarzadeh and dos Santos Coelho 2015)
Performed an assessment of solar-powered organic Rankine cycle system for combined solar heat and power in UK domestic applications.	(Freeman, Hellgardt, and Markides 2015)
Optimized the sizing of a hybrid renewable energy system in Spain. Analyses the LCC and calculates a payback of 18 years.	(González et al. 2015)
Developed a PV power generation plant for remote residential applications in Nigeria.	(Akinyele, Rayudu, and Nair 2015)
Analysed Fresnel lens as a promising alternative to reflectors in CSP, due to its potential to overcome techno-commercial constraints of conventional reflector based CSP.	(V. Kumar, Shrivastava, and Untawale 2015)
Developed a hybrid wind-PV-diesel-battery system sizing tool using an empirical approach, LCC and performance analysis, for an electric power plant in Scotland.	(Gan, Shek, and Mueller 2015)
Studied geographical and temporal differences in electric vehicle range due to cabin conditioning energy consumption.	(Kambly and Bradley 2015)
Performed the optimal sizing of PV / battery/diesel based hybrid system and optimal tilting of the solar array using the artificial intelligence for remote houses in India.	(S B Jeyaprabha and Selvakumar 2015)
Developed a multi-objective analytical model for optimal sizing of stand-alone PV water pumping systems, for irrigation purposes in remote areas in Turkey.	(Olcan 2015)
Analysed the economic feasibility and reduction of a building's energy consumption and emissions when integrating hybrid solar thermal/ PV / micro-combined heat and power (CHP) systems.	(Romero Rodríguez et al. 2016)

Performed the optimal allocation and sizing of PV/Wind/Split-diesel/Battery hybrid energy system.	(Ogunjuyigbe, Ayodele, and Akinola 2016)
Traced the cost roadmap for silicon heterojunction solar cells. Pointed out that research and development of these solar cells have seen a marked increase since the recent expiry of core patents.	(Louwen et al. 2016)
Presented the LCC analysis of passive solar stills by incorporating the effect of energy payback period. Evaluated the exergy economic and energy matrices for the climatic condition of India.	(Singh et al. 2016)
Developed a hybrid electricity supply system for a remote community. Concluded that despite the highest initial cost, its LCC, fuel consumption and carbon footprint are lower than other solutions.	(Akinyele and Rayudu 2016)
Studied the effect of energy matrices on LCC analysis of partially covered PV compound parabolic concentrator (CPC) collector active solar distillation system.	(Singh and Tiwari 2016)
Developed the optimisation of a hybrid solar-wind-powered reverse osmosis water desalination system in Iran.	(Maleki, Khajeh, and Rosen 2016)
Explained the use of solar liquid desiccant regeneration and Nanofluids in evaporative cooling for spaces in high ambient humidity climate, used for greenhouse food production in Saudi Arabia.	(Abu-Hamdeh and Almitani 2016)
Developed a multi-objective differential evolution algorithm-based sizing of a stand-alone PV water pumping system.	(Muhsen, Ghazali, and Khatib 2016)
Presented a method for multi-objective and simultaneous optimisation of energy systems and building envelope retrofit in a residential community in Switzerland.	(Wu et al. 2017)
Demonstrated the possibility to use energy-cost optimal building designs based on life cycle approach. Used a case study building in Finland with three structural alternatives.	(Pal et al. 2017)
Modelled a predictive control of heat pump water heater powered with the integrated renewable-grid energy system. Conducted an LCC analysis.	(Wanjiru, Sichilalu, and Xia 2017)
Developed a smart PV system blind and verifies its impact on nZEB using technical-economic-political analyses.	(C Koo et al. 2017)
Performed an experimental evaluation of an unglazed solar air collector for building space heating in Iraq.	(Al-damook and Khalil 2017)
Analysed the LCC of different heat pump based nZEB concepts for the new detached house and a new apartment building in Finland.	(Paiho, Pulakka, and Knuuti 2017)
Investigated the economic feasibility and environmental impact of energy renovation packages for European office buildings.	(M. Gustafsson et al. 2017)
Studied the establishment of a base price for the Solar Renewable Energy Credit from the perspective of residents and state governments in the US.	(Lee, Hong, Yoo, et al. 2017)
Developed of a double-effect solar still with evacuated tubes for water desalination considered for small-scale applications at remote locations where only saline water or brackish water is available.	(Panchal 2017)
Presented a model for commercial adoption of PV systems in the USA. Studied the impact of government incentive programs and solar PV system LCC on customer adoption.	(W Wang, Yu, and Johnson 2017)
Presented planning and optimisation of DC microgrid for rural applications in India. Perform simulations to determine the optimal system configuration which has the lowest LCC.	(Phurailatpam, Rajpurohit, and Wang 2017)
Examined the LCC effectiveness in using PV solar systems about the number of occupants and consumption for residential dwellings over a 25-year period, in Australia.	(Tam et al. 2017)
Determined priority order of Indian energy sector projects on investments and strategic dimension angle, based on perspectives of LCC and management-thinking approach.	(Soni, Singh, and Banwet 2017)
Performed the LCC analysis for battery energy storage systems (BESS) optimal sizing.	(Marchi, Pasetti, and Zanoni 2017)

Developed an integrated multi-objective optimisation model for determining the optimal solar incentive design.	(Lee, Hong, Kang, et al. 2017)
Compared the cost of operating the auxiliary components of an optimised stand-alone hot water fired absorption chiller, using grid electricity and an optimised stand-alone PV system, in Australia.	(Abdullah, Whaley, and Saman 2017)
Analysed the economic impact of residential progressive electricity tariffs in implementing the building-integrated PV blind. Used a finite element model to simulate the scenarios, in South Korea.	(Oh et al. 2017)

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