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ESCUELA POLITÉCNICA DE INGENIERÍA DE GIJÓN.

GRADO EN INGENIERÍA ELÉCTRICA

ÁREA DE INGENIERÍA ELÉCTRICA

ANALYSIS OF SOLUTIONS FOR ENERGY SELF-SUFFICIENCY OF A SINGLE-FAMILY HOUSE USING RENEWABLE ENERGY

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Resumen

La memoria de este proyecto cuyo título se corresponde a "Analysis of solutions for energy self-sufficiency of a single-family house using renewable energy" fue realizado durante un convenio de estudios tipo Erasmus+, en Lulea University of Technology (Suecia), durante los meses de Enero y Abril, correspondiéndose con el Trabajo de Fin de Grado en Ingeniería Eléctrica.

Durante la última década, la población mundial se está percatando de las graves consecuencias que están trayendo consigo la gran dependencia y consumo de los combustibles fósiles. Es por ello, que numerosos países están volcados con el desarrollo de las energías renovables. Sin embargo, su uso no es una novedad, ya que la energía solar, eólica o la hidráulica se utilizaban desde antes de la I Guerra Mundial pero que debido a diversas circunstancias, su uso se vio desvanecido hasta años recientes donde vuelven a tener un papel crucial para la lucha contra el cambio climático.

España es un país que cuenta con innumerables posibilidades de aprovechamiento de estas energías renovables: eólica (onshore y offshore), solar, hidráulica, biomasa, mareomotriz, undimotriz, etc. Sin embargo, su contribución a la producción de la energía total que es consumida apenas supera el 17% durante el año 2016, pese que existen algunas medidas que obligan a la implantación de paneles solares o colectores en edificios de nueva construcción, por ejemplo.

El objeto del presente proyecto se basa por tanto en buscar alternativas que empleen el uso de energías renovables para su consumo en una vivienda unifamiliar, reduciendo de tal manera, la dependencia de energía procedente de combustibles fósiles, logrando el autoabastecimiento energético. La vivienda objeto de estudio se localizará en la ciudad de Gijón, perteneciente a la provincia del Principado de Asturias, en el norte de España.

Para ello, se hará primero un breve estudio de la situación energética en dicha comunidad autónoma, haciendo un hincapié en el uso del recurso solar y energía eólica. Tras el análisis de los diferentes recursos energéticos que se pueden encontrar en Asturias para la producción de energía eléctrica y térmica, se procederá a realizar un primer diseño de dos tecnologías que emplean la energía solar para la producción tanto de electricidad como energía térmica en la vivienda unifamiliar. En la conclusión del trabajo, se hará un estudio económico que refleje la viabilidad que tendría la implantación de ambos sistemas y futuros trabajos que ayuden a mejorar el presente proyecto.

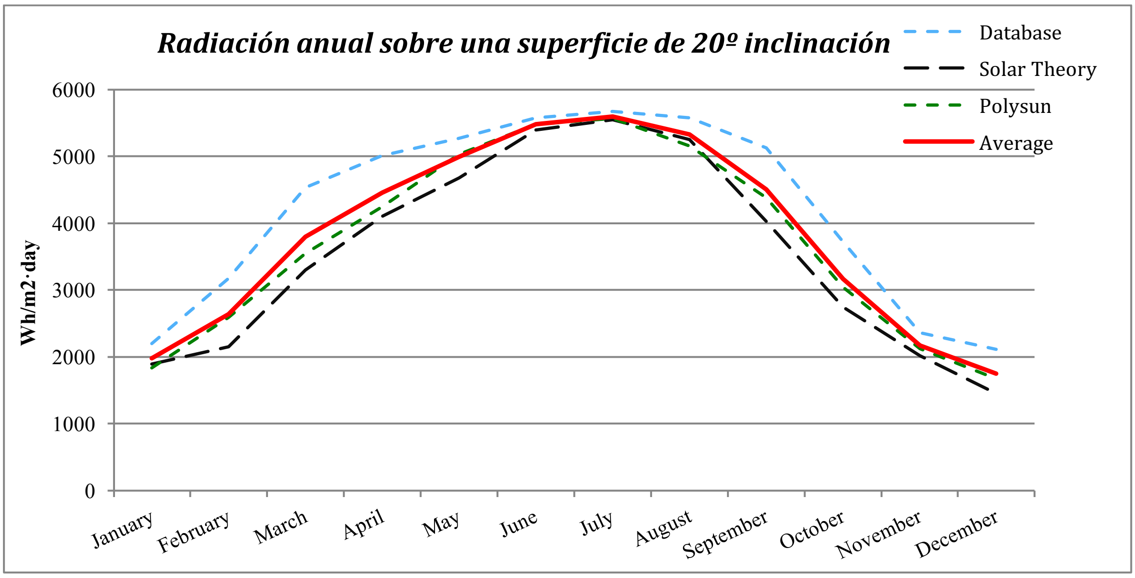
Los datos técnicos, de localización, así como el consumo energético de la vivienda son conocidos, pues se trata de una vivienda real, emplazada en la carretera de Castiello, 537, Gijón, 33394, Asturias.

La situación energética en Asturias estuvo caracterizada durante muchos años por la gran importancia de reservas de carbón, que atrajeron la construcción de centrales térmicas y a la industria del metal, la cual, sigue siendo hoy en día de gran importancia. El análisis energético correspondiente a Asturias reflejará una disminución del autoabastecimiento de energía (renovable) con respecto al año anterior, que continúa

con la negativa tendencia marcada en los últimos años. Esta caída se debe en parte a la menor producción de energía renovable que tuvo lugar en 2015 junto con la bajada de precios de los combustibles fósiles y, antiguamente, la dependencia del carbón. Sin embargo, del análisis, se puede extraer una faceta positiva en cuanto al amplio rango de posibilidades del uso de recursos renovables. Actualmente, la biomasa es la principal fuente de energía renovable, seguida de la energía eólica, que, pese a su gran potencial, ve limitada su desarrollo debido a la existencia de áreas naturales protegidas. Por otro lado, en cuanto a la generación electricidad, el recurso solar apenas tiene uso, dato que impresiona cuando se comparan los valores anuales de radiación solar entre Asturias y Alemania, los cuales son similares. Alemania es el principal país de la UE en producción de energía fotovoltaica. Las razones primordiales del bajo aprovechamiento del recurso fotovoltaico son temas económicos (en el Sur de España es más barato la implantación de paneles FV y su mantenimiento) y políticos.

Por tanto, en este proyecto se describirán dos tecnologías que se basan en la energía solar para lograr el autoabastecimiento energético. En lo que se refiere al consumo de energía térmica para ACS (agua caliente sanitaria) y calefacción, se describirá un novedoso sistema desarrollado y patentado por la compañía noruega Norconsult AB. Este sistema es denominado Active Solar Energy Storage (ASES), se basa en el almacenamiento temporal de energía solar térmica debajo del edificio. Por otro lado, para la producción de energía eléctrica, se implantará un sistema de paneles solares fotovoltaicos que, a su vez, estarán conectados a la Red de Distribución, constituyendo un sistema de energía de balance neto.

Al tratarse de tecnologías solares, es necesario el cálculo de la radiación solar incidente sobre la cubierta de la vivienda, donde se colocarán los paneles y colectores solares. Para ello, se realizó un valor medio de los datos obtenidos al hacer un modelo matemático que calcula mensualmente, la radiación incidente sobre una superficie con una determinada inclinación en un día medio, y datos obtenidos del software de simulación Polysun y de una base de datos europea.



El sistema ASES es, por tanto, un sistema que emplea directamente la energía solar, la cual es captada a través de unos colectores solares planos ubicados en la cubierta de la vivienda. Éstos colectores calientan un fluido que circula por unas tuberías en su interior, las cuales, calientan agua de un depósito en el interior de la vivienda, el cual es utilizado para su uso como ACS. Este sistema es optimizado para el almacenamiento temporal de energía solar térmica. El exceso de energía que es producida durante nos meses de verano principalmente, es almacenada debajo de los cimientos de la vivienda mediante unas tuberías. Este calor es posteriormente utilizado durante los meses de invierno mediante una bomba de calor para el suministro de calefacción. El sistema de calefacción empleado es el de suelo radiante, ya que necesita de una temperatura del agua alrededor de 45-50°C, aumentando así la eficiencia del sistema.

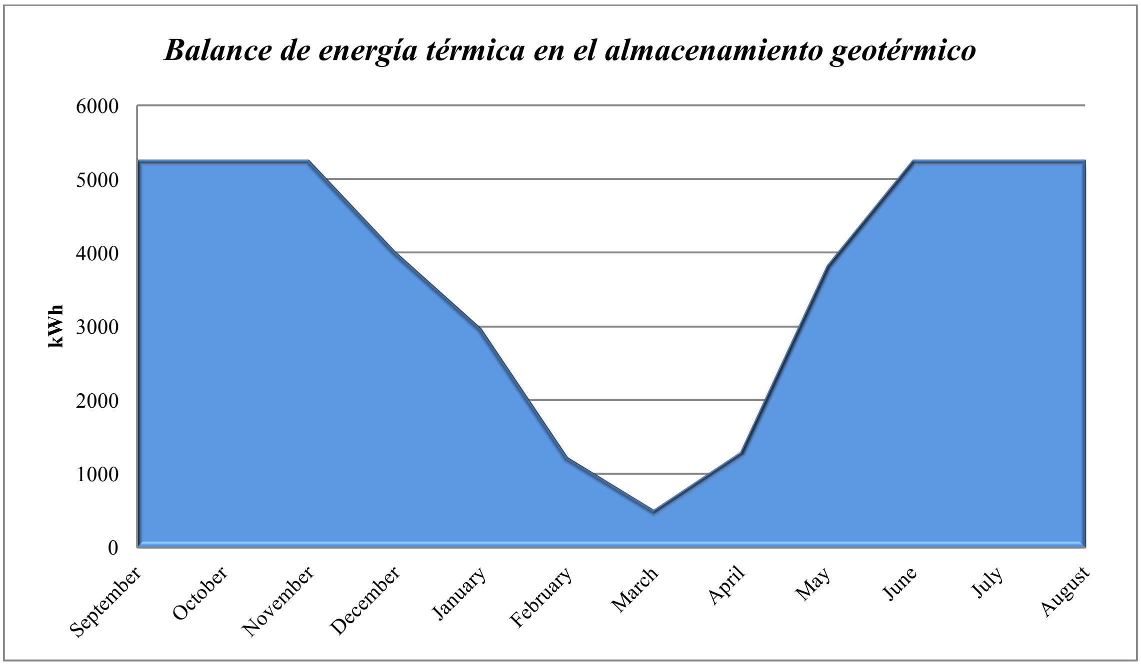
El almacenamiento geotérmico es construido con una gran cantidad de polvo de piedra debido a sus propiedades térmicas. Para su diseño se emplea el software Fluent, el cual nos permite simular los gradientes de temperatura que tienen lugar durante cada mes, debido a las diferentes temperaturas del agua que circula por los conductos, la temperatura ambiente, y una mínima variación de la temperatura del terreno. Con ello, se podrá estimar los valores límite de energía que el almacenamiento es capaz de almacenar.

El sistema de captación solar del ASES se constituirá de 10 colectores solares planos que estarán en la cubierta de la vivienda con un ángulo de inclinación de 20° con respecto al horizontal y orientados al Sur. Las características de los colectores no corresponden a una marca en concreto, sino que son parámetros medios que se pueden encontrar fácilmente en el mercado. El cálculo de la energía que es captada por éstos se realiza mediante un modelo matemático, que permite, conociendo los valores de consumo de la vivienda, calcular la energía solar térmica que es aportada mensualmente al almacenamiento geotérmico, así como los valores de eficiencia, obteniendo un valor medio anual de la eficiencia de los colectores de un 38%.

Como se comentó recientemente, con el software Fluent se puede analizar el comportamiento en el almacenamiento. Éste presenta diferentes gradientes de temperatura a lo largo del año, es en lo que se basa fundamentalmente el sistema ASES. Es decir, durante los meses de verano, el agua que es introducida por los conductos al almacenamiento, produce un incremento de temperatura en la tierra. Esto hace que, durante invierno, se produce un intercambio de calor entre la temperatura de la tierra y la temperatura del agua que circula, y que, mediante una bomba de calor, es extraída para el aporte de energía. Lo que se consigue es un menor empleo de energía por parte de la bomba, reduciendo así su consumo e incrementando la eficiencia total del sistema. Además, se conocerá los valores límites de diseño del almacenamiento, es decir, cuánta energía es capaz de acumular desde el período de verano hasta invierno.

Combinando este modelo de simulación junto con el modelo matemático de los colectores solares, nos permite apreciar que se produce un exceso de energía desde Junio hasta Noviembre. Esto significa que el almacenamiento está a su máxima capacidad y que no se está aprovechando toda la energía que los colectores están produciendo. En futuros trabajos y análisis de optimización de este sistema se encargarán de esta situación, ya que existen diferentes posibilidades como la desconexión de algunos colectores, otros usos del exceso de calor o el aumento de las

dimensiones del almacenamiento, ya que, tras esta pérdida de calor, el aprovechamiento del sistema se ve disminuida. Por otro lado, se apreciará que durante el mes de Marzo será cuando haya menos energía sin llegar a los valores límite. Eso implica que el sistema ASES es capaz de suministrar, con la ayuda de la bomba de calor, el 100% de la demanda energética para calefacción y ACS, sin necesidad equipos auxiliares. Sin embargo, hay que tener presente que los resultados obtenidos se corresponden al primer año de simulación considerando que las condiciones meteorológicas son similares a las consideradas (correspondientes al año 2016). Es decir, al ser una tecnología que depende principalmente de la incidencia de rayos solares y de la temperatura ambiente, si ocurriera una gran disminución de temperaturas, el almacenamiento quedaría expuesto a no cubrir la totalidad de la demanda, requiriendo un sistema auxiliar.



Por otro lado, como se comentó brevemente, para el suministro de electricidad a la vivienda, se empleará un sistema de paneles fotovoltaicos, constituido por 16 paneles, a 20° de inclinación colocados en la cubierta con orientación Sur. Este sistema, a diferencia del ASES, no cubrirá la demanda total de electricidad, lo cual, este sistema estará conectado a la red de distribución. Con esta configuración se habilitará el aporte a la red del exceso de electricidad generada por los paneles FV en sus horas pico. Al igual que el consumo de energía de la red cuando los paneles no son capaces de suministrar la demanda. Otra opción hubiera podido ser el uso de baterías eléctricas que almacenasen la energía, sin embargo, se decantó por la primera configuración ya que es un sistema eficazmente conocido y está más legalizado que el segundo.

Cada panel FV tendrá una potencia pico de 240 Wp (potencia total de 3840 W). Como se hizo con los colectores, las características (dimensiones, parámetros eléctricos, …) son valores medios de diferentes paneles que se pueden encontrar hoy en día en el mercado. De esta manera, y al tratarse de un proyecto de análisis e investigación, se podrá hacer una estimación inicial del uso del recurso fotovoltaico.

Los mayores inconvenientes de este sistema fotovoltaico son su dependencia a las condiciones meteorológicas y al consumo horario en la vivienda. Generalmente, el consumo eléctrico es alto en las primeras horas de la mañana y en la noche. Durante estos períodos, la producción fotovoltaica es mínima o nula. Es por tanto por lo que se considera una configuración de energía de balance neto, donde el sistema al estar conectado a la red, permite satisfacer las demandas en esos períodos de tiempo. En cambio, cuando la producción FV es mayor, la demanda es menor, luego el exceso de energía es vertido a la red. De esta manera se consigue una mejor eficiencia y reducir la factura de la luz (se consume menos energía de la red). Sin embargo, los beneficios se verían incrementados si las Leyes y medidas políticas del gobierno español fueran favorables al desarrollo e implementación de la energía solar fotovoltaica, así como al desarrollo de la generación distribuida, ya que el aporte propio de la energía que es producida en la vivienda y es introducida en la red, no tiene ningún beneficio. En cambio, en otros países europeos, este aporte de energía se ve beneficiado con un aporte económico.

Los datos obtenidos de la producción eléctrica son obtenidos del software de simulación Polysun. Los resultados reflejan que no es posible cubrir el consumo total, lo cual es necesario un equipo de suministro auxiliar, en este caso, será la red de distribución. Se puede apreciar también que entre finales de Mayo y Septiembre, el consumo eléctrico disminuye mientras que la generación FV aumenta, debido a una mayor radiación solar incidente sobre los paneles. En total, se puede llegar a producir hasta un 65% del consumo anual. Sin embargo, será necesario en futuros trabajos el diseño de sistemas de optimización que se basen en compensar las diferencias horarias entre la producción de electricidad y su consumo en la vivienda, así como la exposición a posibles cambios bruscos en las condiciones meteorológicas.

Una vez explicados y analizados las dos tecnologías empleadas para el uso de energía solar para satisfacer la demanda energética, se procede a realizar un estudio económico. Pese que los valores no son exactos, servirán como una primera idea de la viabilidad de los sistemas. Para ello, se calcula el importe anual que conlleva el consumo de la vivienda, y, por otro lado, la inversión inicial. Para la inversión, al igual que con las placas y colectores solares, se consideraron valores medios. En total, la inversión inicial conjunta de ambas tecnologías alcanza 18.724,6€, considerando que no hay ningún tipo de subvenciones. La reducción económica es posteriores años se verá reflejada por la disminución de la factura, la cual en el año 2016 asciende a 2.301,25€. Para ello, se realiza un estudio durante los primeros 25 años de uso de las tecnologías, considerando diferentes parámetros económicos: precio electricidad, precio gas natural, impuestos, costes de mantenimiento; parámetros técnicos: disminución de las eficiencias. El estudio económico se calcula mediante el cálculo del valor actual neto (VAN), la tasa interna de retorno (TIR), y el pay-back (período que tarda en amortizarse la inversión inicial).

Considerando todos los parámetros necesarios para una primera estimación, se obtiene que el TIR es de 9,64%, lo cual significa que las instalaciones de los sistemas son económicamente viables ya que es superior a la tasa considerada del 5%. Por otro lado, el período de amortización se establece en 10 años, lo cual, considerando que el estudio se basa en un tiempo de 25 años, la inversión inicial es amortizada en menos de la mitad de período.

Estudio Económico	
Payback [años]	10
VAN	23.916,37 €
TIR	9,64%

A instancias de los resultados obtenidos tras los cálculos de las dos tecnologías descritas, basadas en la energía solar, se puede concluir que son sistemas energéticamente y económicamente viables para la producción de energía, tanto eléctrica como térmica, en una vivienda unifamiliar. Sin embargo, existen una serie de factores de gran importancia que intervienen en su desarrollo. El principal de ellos es la condición meteorológica. Los resultados obtenidos serán más o menos reales, si las temperaturas y la nubosidad durante los 25 años tienen valores similares a los considerados para el año 2016. Además, otro factor de importancia y el cual, es el más preocupante hoy en día, son las medidas y leyes políticas existentes en España, que dificultan en su medida el desarrollo de las energías renovables, especialmente la solar, para su autoconsumo. Si bien es cierto España trata de lograr las medidas pactadas en el famoso "Protocolo de Kyoto" con el "20,20,20", no favorece el desarrollo de la energía solar, en concreto la fotovoltaica, la cual tiene un impuesto especial para aquellas personas que instalen placas fotovoltaicas para su consumo. Esta medida del gobierno, conocida como "el impuesto al Sol", ha sido muy criticada por la sociedad, ya que no se conoce ningún otro país que aplique un impuesto por el aprovechamiento de la energía solar, el cual es un recurso disponible en la mayoría del mundo y para toda sociedad.

Es por tanto que, en la finalización de este proyecto se pueden concluir 3 ideas principales:

a) El consumo de energía convencional en el sector residencial puede ser reducido con la implementación de estas tecnologías.
b) Las tecnologías descritas basadas en el recurso solar son energéticamente y económicamente viables.
c) Es de necesidad aplicar leyes y políticas por parte del Gobierno español que favorezcan el desarrollo de las energías renovables.

Para concluir el presente proyecto, se hace una breve reflexión sobre futuros trabajos que ayuden a mejorar y optimizar estos sistemas. Esto pasaría por determinar las horas diarias en las cuales se produciría un mayor consumo de energía con la menor producción de esta, y lo contrario. El otro condicionante al cual habría que buscar una solución es la intermitencia de la disponibilidad de energía solar. Para ello, actualmente existen posibles soluciones como la adición de almacenamiento de energía eléctrica, como son las baterías o pilas de hidrógeno. Entonces, habría que mejorar sus eficiencias.

En el otro lado, refiriéndose al tema social, estaría la eliminación de los impuestos que presentan las energías renovables, y su consiguiente desarrollo con nuevas medidas, favoreciendo con subsidios o aplicando impuestos más estrictos a las energías procedentes de combustibles fósiles.

Es por tanto que, este proyecto se inició con la idea de describir dos tecnologías basadas en la energía solar que contribuyeran al autoconsumo energético en una vivienda unifamiliar emplazada en la localidad de Gijón. En su finalización, se puede concluir que los objetivos iniciales se han cumplido y que los sistemas son factibles, pero, por otro lado, futuros trabajos de optimización en estos sistemas, la dependencia del Sol y las medidas políticas serán los factores que marquen la viabilidad de estas tecnologías en el futuro.

For my parents and brother,

who where always by my side giving me support.

Abstracto

La realización de este proyecto se llevó a cabo en la Universidad Tecnológica de Lulea (Suecia), durante los meses de Enero y Abril de 2017. Este trabajo está validado como Trabajo Fin de Grado en Ingeniería Eléctrica por parte de la Universidad de Oviedo, España.

La finalidad de este trabajo es, analizar la viabilidad energética y económica de la posibilidad de diseñar e instalar dos tecnologías de energías renovables, para satisfacer la demanda energética en una vivienda unifamiliar situada en la ciudad de Gijón. El aumento de los precios de la energía, y la limitada existencia de combustibles fósiles, están forzando a buscar alternativas para alcanzar el autoconsumo energético en el sector residencial. El futuro estándar para la construcción de edificios, se basa en edificios de energía neta cero (NZE). Este proyecto utiliza una vivienda unifamiliar que utiliza gas natural para calefacción y agua caliente sanitaria (ACS), y toda la electricidad demandada proviene de la red de distribución.

Se han diseñado y analizado dos tecnologías renovables diferentes. Ambos se basan en recursos de energía solar. Para la calefacción y ACS se estudió el almacenamiento activo de energía solar mediante el sistema ASES, y los resultados han reflejado que el 100% de la demanda de calefacción puede ser cubierto en condiciones óptimas con los datos considerados durante el primer año. En el caso de la alimentación de electricidad, se realizó un análisis de la colocación de paneles fotovoltaicos en la cubierta de la vivienda. Se consideró un sistema fotovoltaico conectado a la red de distribución. En condiciones óptimas, los paneles solares pueden llegar a producir hasta el 65% del consumo anual.

Los sistemas combinados corresponden aproximadamente el 80% de ahorro de toda la electricidad y el calor comprados que son necesarios para mantener el mismo estilo de vida dentro de la vivienda. Para hacer el estudio económico, una inversión inicial fue abordada haciendo una investigación de mercado sobre los costos de tecnologías y materiales disponibles sin especificar ninguna marca. El análisis concluyó con un período de amortización de 10 años después de la instalación de ambos sistemas. Sin embargo, este es un proyecto de investigación. Las condiciones y parámetros asumidos pueden variar dependiendo principalmente de las condiciones climáticas. El trabajo posterior, que trata de la optimización de estas tecnologías y el diseño de soluciones para superar la intermitencia de la energía solar y las futuras políticas del Gobierno, reflejará la rentabilidad real.

Abstract

This project was conducted at Luleå University of Technology, Sweden, between January and April of 2017 and is validated as the Bachelor Thesis Degree in Electrical Engineering by the University of Oviedo, Spain.

The purpose of this work is to examine how viable, energetically and economically, would be to design and install two renewable energy technologies to cover heating and electricity demands for a single-family house in the city of Gijón, in the north of Spain. The increase in energy prices and limit existence of fossil fuels are forcing to look for alternatives to reach energy self-consumption in the residential sector. The future standard for building construction is based on near-zero energy (NZE) buildings. The project has a depicted single-family house that uses natural gas for heating and tap water and all the electricity is feed from the distribution grid.

Two different renewable technologies have been designed and analyzed. Both are based on solar energy resource. For heating, the Active Solar Energy Storage (ASES) was studied and results have reflected that 100% of the heating demand can be covered in optimal conditions with the data considered during the first year. In the case for feeding electricity, analysis of placing PV panels on the roof was done. It was considered a photovoltaic grid-connected system. In optimal conditions, solar panels can produce up to 65% of annual electricity consumption.

Systems combined correspond to about 80% savings of all purchased electricity and heat needed to maintain the same life style inside the house. To make the economic study, an initial investment was approached doing a market research about the technologies and materials costs available without specifying any brand. The analysis concluded with a payback period of 10 years after the installation of both systems. However, this is a research project. Conditions and parameters assumed may vary depending mainly on weather conditions. Further work, dealing with optimization of these technologies and design of solutions to overcame the intermittency of solar energy and future Government policies will reflect the real profitability.

Universidad de Oviedo EPI GIJÓN

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Nomenclature

Standard longitude	L_{St}	[˚]
Longitude	L_{long}	[˚]
Latitude	φ	[˚]
Earth albedo	P_g	[-]
Solar collector area	A	[m^2]
Collector heat removal	F	[-]
Cloudiness	C	[%]
Declination	δ	[˚]
Solar constant	G_{SC}	[W/m^2]
Extraterrestrial radiation	$G_{0,n}$	[W/m^2]
Day number	n	[-]
Absorber surface	S	[W/m^2]
Azimuth angle	Υ	[˚]
Solar time	t	[h]
Hour angle	ω	[˚]
Incidence angle	θ	[˚]
Zenith angle	θ_Z	[˚]
Tilt of solar collector	β	[˚]
Irradiation	I	[Wh/h]
Irradiation, diffuse	I_d	[Wh/h]
Irradiation, beam	I_b	[Wh/h]
Irradiation, diffuse on a tilted area	I_{dT}	[Wh/h]
Irradiation, beam on a tilted area	I_{bT}	[Wh/h]
Irradiation, reflected	I_{rT}	[Wh/h]
Irradiation, tilted area	I_T	[Wh/h]
Beam component	R_b	[-]
Diffuse component	R_d	[-]
Reflective component	R_r	[-]
Clearness index	K_t	[-]
Seasonal Coefficient of Performance	SCOP	[-]
Heat carrier temperature	T_v	[K]
Heat loss coefficient	U_l	[W/m^2K]
Optical efficiency	h_0	[%]
Useful energy	Q_u	[W]
Heat losses	Q_f	[W]

1. Introduction

1.1- Background

Since the end of the 20th century the world population has been warning of the consequences of the traditional energy model based on the draining of natural resources, especially as regarding the environment, with a growing concern for the planet and the future of humanity. It is already a fact that fossil fuels have an end date. That is why there are many investigations and developing ways to replace them by renewable energy sources, trying to contribute to a sustainable development. This is leading to a transformation in the energy sector, where the weaknesses of the traditional system are being addressed, favoring the growth of renewable energy and improving energy efficiency.

From just being an experimental technology some years ago, solar energy has gone through a striking learning curve. Now is able to be competitive without subsidies in an increasing number of markets. Solar panels have become a common prospect on buildings and ground installations. The new solar energy keywords are self-consumption (the consumption by the household of locally produced solar energy) and self-sufficiency (the capability to autonomously meet the energy demand of the household). To achieve these two aims, the misalignment between the daily solar power profile and the household demand must be overcome.

In the framework of thermal energy, it is also being opting to implement small independent systems with low power that can generate heat by using solar collectors. The excess heat produced is generally stored in water accumulator tanks for later use. The main drawback of these systems is that cannot maintain enough energy needed during the months with lower solar energy supply, specially in winter seasons.

The aim of these actions is to improve energy efficiency and promote the use of renewable energy sources to increase security in energy supply, reduce energy costs and endorse a better environment for all citizens and with these, reduce GHG emissions.

1.2- Motivation

Spain is in a situation where the current trend is to understand energy saving and efficiency as a way of economic growth and social well-being. This energy saving is motivated from the state's administration, in the form of regulations and plans to that effect. In the specific case for residential sector, the main reference points are the Technical Building Code (CTE) through its basic energy saving requirements (HE) and the Renewable Energy Plan for Spain 2011-2020 (PER). [14]

Through renewable energies, energy savings are obtained by reducing the use of conventional energy sources. A complementary strategy for the intensive use of renewable energy sources is the reduction of energy demand. Reducing demand in family houses without penalizing the thermal comfort is one of the measures on which there is room for operation. It is also compatible with a future sustainable scenario and with a lower degree of energy dependence. [20]

The total solar radiation that reaches the Earth's surface is more than enough to supply the world's total energy needs. However, matching the discontinuous availability of this energy source with demand presents a challenge, especially in the beginning of the day and evening hours, because solar energy sources do not produce enough power to fulfill all the demand. This challenge can be overcome by energy storage: coupling solar energy sources (electrical and thermal) with energy storage can remove the unpredictable nature of solar energy. [21]

The motivation of this project is to encourage the use of renewable energy resources and reduce the consumption of exhaustible conventional energies. At the same time, since CO_2 emissions are hand in hand with these consumptions, it would be possible to reduce the environmental impact that is caused contributing to reduce climate change.

1.3- Solar energy technologies

This research project proposes the application of renewable energy technologies to meet thermal energy demands (heating a domestic hot water) and part of the electricity in a single-family house. These technologies will be based in solar power, taking advantage of the solar thermal and photovoltaic energies.

Among different solar thermal technologies that are available, an innovative system will be considered: Active Solar Energy Storage (ASES). In active solar heating systems, a fluid is heated by using solar energy and then transfer the solar heat directly to the interior space or to a storage system for later use. When the solar system cannot provide adequate space heating, an auxiliary system provides the additional heat. Liquid systems are more often used when storage is included and are well suited for radiant heating systems. Flat-plate collectors are the most common, but evacuated tube and concentrating collectors are also available. [26]

For the heating system, radiant floor will be considered. In this type of system, solar-heated liquid circulates through pipes embedded in a thin concrete slab floor, which then radiates heat to the room. Radiant floor heating is ideal for liquid solar systems because it performs well at relatively low temperatures. [26]

Also, solar photovoltaic energy is going to be studied to feed electricity to the house. However, in this situation, a grid-connected system has been considered. This type of system allows powering the house with renewable energy during those periods when the sun is shining. Any excess of electricity produced is fed back into the power grid. When renewable resources are unavailable, electricity from the grid supplies the house needs, eliminating the expense of electricity storage. Figure 1.1 represents a basic scheme of a photovoltaic grid-connected system, where electricity is produced by PV modules and then, either is consumed or poured into the power grid.

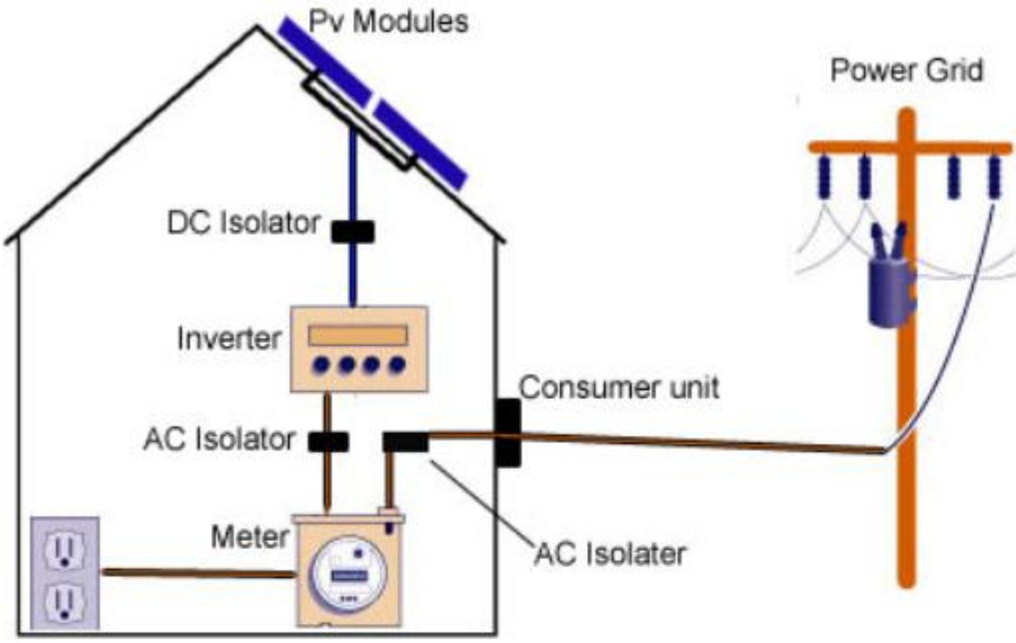

Figure 1.1- Scheme of a photovoltaic grid-connected system for a single-family house with net metering. [31]

There are some countries in where, power providers allow net metering by means of an arrangement where the excess electricity generated by grid-connected renewable energy systems turns back the electricity meter as it is fed back into the grid. If during a month, more electricity than the one that the system feeds into the grid is used, power provider will charge only for the difference between the energy used and the produced.

1.4- Purpose and objectives

The global purpose sought within this project is to study renewable energy alternatives available in the region of Asturias trying to exploit them from the point of view of energy generation in the most efficient way possible, in line with the objectives and international commitments that Spain should meet in the future. To reach the main objective, several aims have been stated and completed throughout this project:

1. To make an analysis of the current energy situation in the province of Asturias.
2. To design a 2-D model thermal storage for the ASES system considering the non-linear temperature distribution to determine the ground temperature.
3. To design a photovoltaic grid-connected system.
4. To design an ASES system determining the number of solar collectors needed.
5. To make a viability and economical study, calculating the net present value (NPV) and internal rate of return (IRR), reflecting the payback period.

1.5- Limitations and assumptions

- The house will have a net energy metering system, connected to the electrical distribution grid.
- It will not be considered the electrical companies to which the electricity will be sell/ buy. Only it will figure that the installation is connected to the electrical grid.
- The solar collectors and PV panels would be placed in the roof of the single-family house with an inclination of 20°.
- The technical calculus is done based on the Technical Conditions of Connected Installations Network.
- The installation costs will be estimated by a comparison of the materials available in the market.
- The economical calculation will be based in series of parameters chosen in such a way the results obtained are coherent with the study. It will conclude with the calculation of the payback time.
- No cooling system is considered.
- It has not been considered the time difference between solar energy production and house consumption.

1.6- Location

An important thing to consider when studying the use of renewable energy sources is the potential that the location should take advantage of those sources. For this project, the single-family house would be located in Gijón, a city in the province of Asturias, in the northwest of Spain.

Latitude and altitude of Gijón are: 43°32’00” N, 5°42’00” W. These two parameters are essential to determine the available solar radiation.

Figure 1.2- Renewable energies may help depending on the location. This project is focused in Gijón, in the northwest of Spain [11]

2. Theory

2.1- Energy situation in Asturias

The province of Asturias has a unique energy structure due to several factors, characterized by the existence of numerous coal deposits that have attracted the presence of coal-fired power stations. For this reason, in the 1980s, an important industrial activity emerged characterized by a high intensity on the energy consumption, as in the case of the steel industry, which nowadays remains being one of the most important industries.

According to table 2.1, at regional level, during year 2015, the growth trend in relation to the primary energy consumption continued, with a variation of +15.1% over the previous year, requiring a total of 6.87 Mtoe. [4]

	Primary energy consumption 2014 [Mtoe]	Primary energy consumption 2015 [Mtoe]	Rate 2015/2014
World	13,020.6	13,147.3	1.0%
Europe	1,605.7	1,630.9	1.6%
Spain	118.5	123.6	4.3%
Asturias	5.97	6.87	15.1%

Table 2.1. The growth trend in relation to primary energy consumption continued in 2015 [4]

The energy structure in the Principality of Asturias has been characterized by a greater contribution of coal and natural gas in relation to the previous year because of the lack of renewable energy. The rest of the consumption is distributed between hydropower, fuels and renewable energies as can be seen in figure 2.1.

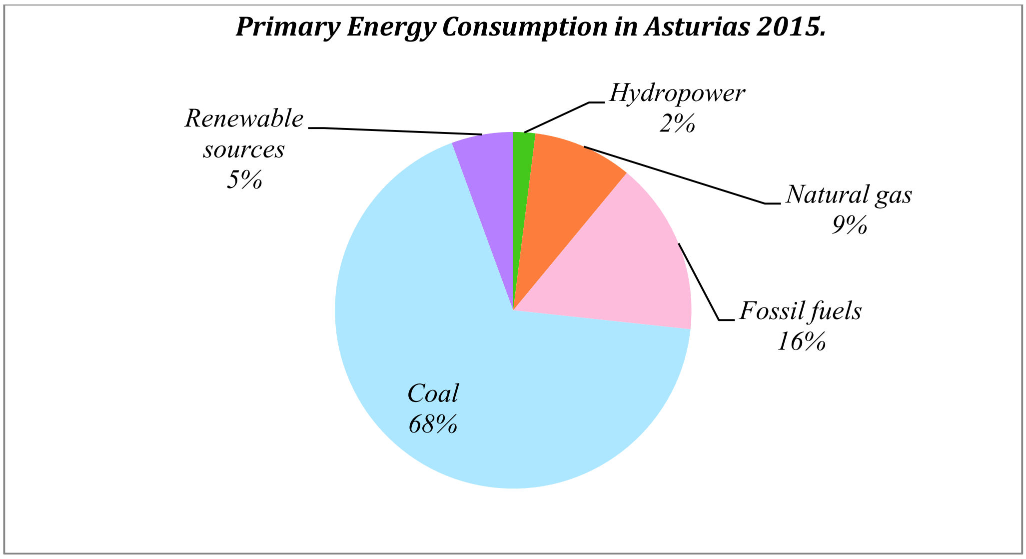

Figure 2.1. Distribution of primary energy consumption in Asturias during 2015 where coal is still the main energy resource. [13]

The increase in consumption of primary energy was due to the increase in coal and natural gas consumptions. Annual variations of different energy resources are presented in table 2.2, where increase in coal and natural gas consumptions represent an annual variation of +28.3% and 3.1% respectively. This was caused by the intensification in the activity of the Asturias thermal power plants. [13]

	Coal [ktoe]	Fossil Fuels [ktoe]	Natural gas [ktoe]	Hydropower [ktoe]	Renewable energies [ktoe]	Total [ktoe]
2015	4,656	1,081	616	139	383	6,874
2014	3,628	1,178	596	164	406	5,972
Rate 2015/2014	+28.3%	-8.3%	+3.1%	-15.2%	-5.6%	+15.1%

Table 2.2. Annual energy resources variations of primary energy consumption in Asturias [13]

In relation to final energy consumption, natural gas and electricity produced in hydropower plants have increased with a deviation of +3.5% and +2.9%, respectively, due to a higher consumption in the industry and services sector as is stated in table 2.3.

	Coal [ktoe]	Fossil Fuels [ktoe]	Natural gas [ktoe]	Hydropower [ktoe]	Renewable energies [ktoe]	Total [ktoe]
2015	1,427	971	502	865	163	3,928
2014	1,235	1126	495	840	173	3,859
Rate 2015/2014	+15.6%	-13.7%	+3.5%	+2.9%	-5.9%	+1.8%

Table 2.3. Final energy consumption from different energy sources in Asturias [13]

- <u>*Rate of self-sufficiency*</u>

The rate or degree of self-sufficiency is defined as the relation between the production of autochthonous primary energy and the consumption of primary energy. In 2015, Spain obtained a degree of self-sufficiency around 26.9%. This means a decrease of 7.9% with respect to 2014. [13]

$$Self-sufficiency\ (\%) = \frac{\begin{array}{c}Primary\ native\\ energy\ production\end{array}}{Primary\ energy\ consumption}$$

In Asturias, energy sources that are autochthonous are coal and renewable energies such as hydropower, biomass, wind power, solar thermal and photovoltaic. The rate of self-sufficiency in Asturias during 2015 declined to 12% with a variation regarding the previous year of -2.7%.

Figure 2.2 represents the evolution of self-sufficiency rate in Asturias during the last 25 years. It is important to notice that rate at the end of 20th century was three times bigger than recent years. The difference remains in the high production that coal and mining sources used to have in the energy sector.

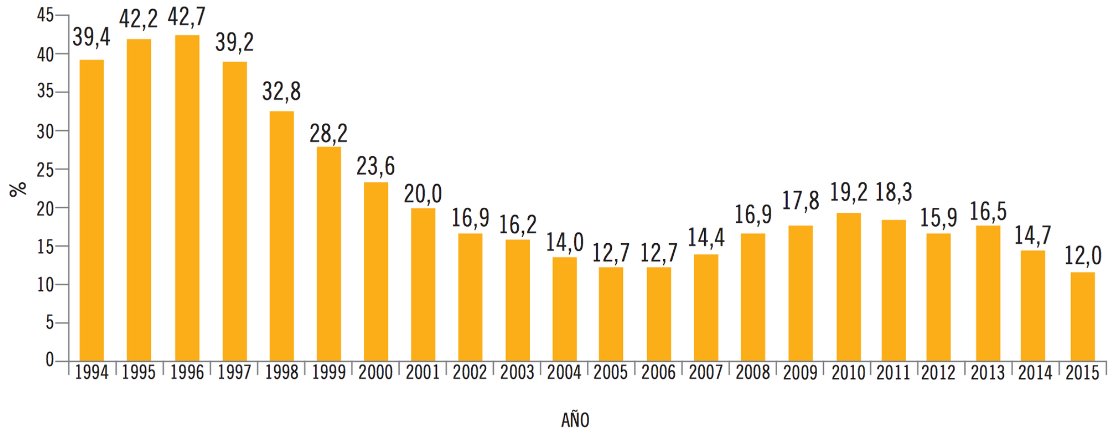

Figure 2.2. The degree of self-sufficiency in Asturias has been decreasing in recent years due to the lack of production of renewable energies [13]

- <u>*Residential sector*</u>

The residential sector is a key in the current energy perspective, due to the importance of its energy needs. In terms of final energy, in Asturias means 8.3% of the total final energy consumption. During 2015, energy consumption in the residential sector has decreased with a variation of 8.5%, reaching 327 ktoe. This decrease has been influenced mainly by climate conditions. [14]

It is worth noticing the decrease in the consumption of natural gas in this sector, which has represented a change of -23.3% in comparison with the same period of previous year. High temperatures have marked this high variation during the last quarter of the year. Agreeing data published by AEMET, last December 2015, was one of the hottest winter months that have been known in the Principality of Asturias. [14]

On the other hand, electricity consumption has risen to 122 ktoe, meaning an increase of +2.9% compared to 2014. Table 2.4 shows a comparison of the use of different energy sources on final energy consumption within residential sector.

	Coal [ktoe]	LPG [ktoe]	Fossil Fuels [ktoe]	Natural gas [ktoe]	Electricity [ktoe]	Biomass [ktoe]	Solar [ktoe]	Total [ktoe]
2015	30	13	35	121	122	3	3	327
2014	22	13	35	158	119	8	3	358
Rate 2015/2014	+32.5 %	+1.9%	+1.6%	-23.3%	+2.9%	-59.0%	+1.0%	-8.5%

Table 2.4. Within residential sector, electricity and natural gas predominate in the final energy consumption in Asturias [14]

- *Renewable Energies*

To conclude with the energy situation, an analysis of renewable energy resources available in the region of Asturias is done. The objective is to evaluate the different alternatives to face energy generation, mainly electricity.

The contribution of renewable energies to the energy consumption structure during 2015 was 522 ktoe, which had covered 7.5% of the primary regional consumption. However, it has decreased -8.4% compared to previous year. In figure 2.3, the distribution of renewable energies used as primary energy is represented. Biomass is the main renewable resource used thanked to the climatic conditions in Asturias that favors the high existence of forests and crops. However, the contribution of solar energy is minimum. Therefore, throughout this project, it will try to find an alternative to increase the percentage of solar energy for future years. [13]

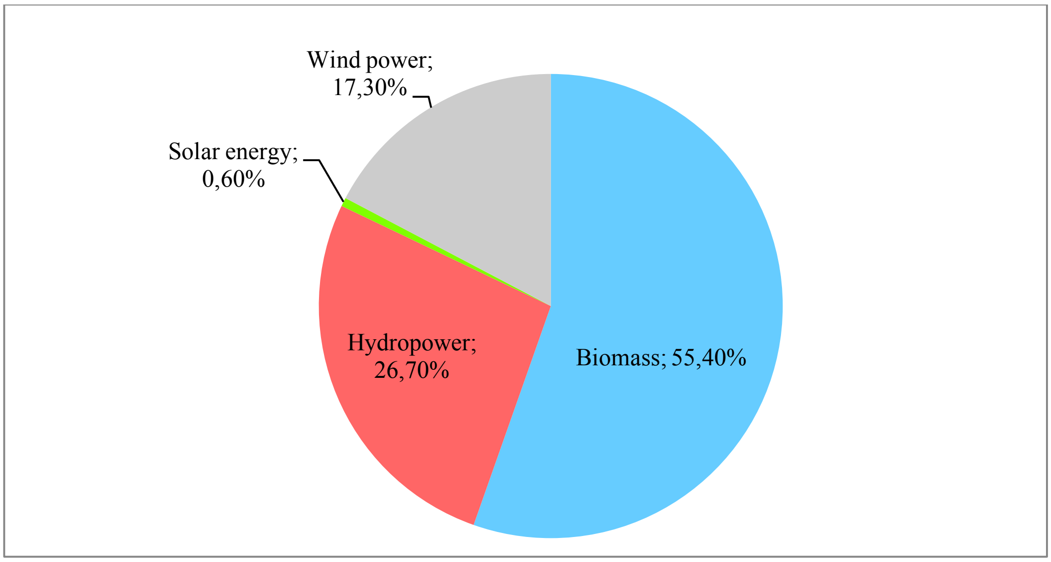

Figure 2.3. Biomass is the main renewable source used as primary energy in Asturias followed by hydropower and wind power [13]

According to the community commitment on energy efficiency, environment and renewable energy, Directive 2009/28/CE, establishes for Spain the objective of 20% contribution with renewable sources to the consumption of final energy by year 2020.

The Spanish Ministry of Industry, Energy and Tourism has published that the contribution in 2015 of renewable energy to the final consumption in Spain was 17.4%. The Principality of Asturias contributed to the national group with 0.5%. [13]

The main renewable energy sources that can be found in Asturias are:

⇒ *Wind Power*

The development of wind power is, probably, the close future for the region regarding the electricity generation. Wind power generation onshore in the Principality of Asturias is focused in the west side and in the Cantabrian Mountains, where the potential is higher as can be seen in figure 2.4.

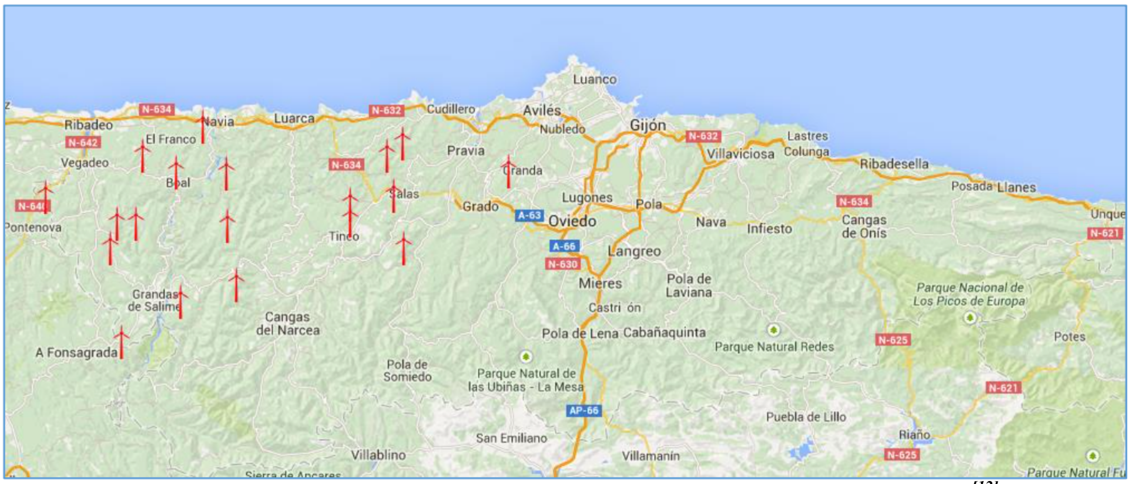

Figure 2.4. Wind farms installed in Asturias are focused on the west side and Cantabrian Mountains [12]

Despite the participation of wind power is still of little relevance and intermittent, the forecasts for future development are advantageous with a projection of improvement in the installed capacity set by the energy plans for year 2020. For this year, is expected that the installed power reaches 900 MW. IDAE has carried out a technical study at national level for the development of renewable energies. The aim of the study was the energy program with horizon 2020, where the data and conclusions are reflected in the "Wind Atlas of Spain". *[13]*

After several studies and researches on the onshore wind resource, it has been estimated that for an area to be usable, one condition to fulfill is that average wind speed should be at least 6.0 m/s at a height of 80 m. This parameter was considered as a reference for the wind resource for a wind farm project to be technically and economic viable. According to data collected in the IDAE report, with this condition, 39.66% of the region would be available to install wind farms. This value is much higher than the actual wind farms surface, which is 22.96%.

One of the reasons of the difference in the surface installed is because the Principality of Asturias is characterized for its large protected area like Protected Natural Areas. These areas exclude the implementation of wind farms. The surface occupied by Protected Natural Areas reaches 22.37% of the total surface in the region (the national average is 9.27%). It gives an idea of the importance and environmental wealth that Asturias has, with a variety of ecosystems that need special protection for their biodiversity. *[12]*

After the application of more criteria such as the altitude of the surface, natural areas, proximity to cities and electricity networks, it is concluded that only 11.60% of the total surface of Asturias (1231 km^2) would be able to take advantage of wind power. In this situation, the value is lower than the Spanish average, which reaches 16.42%.

⇒ *Hydropower*

Asturias region is characterized by being very mountainous and close to the Cantabrian Sea. This geography favors the existence of short and flowing rivers, creating favorable sites for creation of reservoirs. These locations are where hydropower plants are placed.

Currently, there is a delay on the construction of new hydropower plants. Therefore, the investment must be made through the rehabilitation of old non-operative facilities and the repowering and modernization of others. These works should not mean environment deterioration. [14]

One of the alternatives to achieve the objectives set in the contribution of renewable energies to the whole of generation is the use of minihydraulic facilities where possible. The construction of this type should be done using the special generation regime.

⇒ *Solar Energy*

Together with wind power, solar energy is the most important renewable soure at high scales. Although development of solar energy might seem to be economically unviable in Asturias because lack of investments, and politics have focused on other types of renewable energies such as biomass or wind power, data reflects that values for annual solar radiation in the region are quite similar to Germany ones as can be seen in figure 2.5. Germany is a country with high development in solar technology and the European leader, with values close to 1085 kWh/kWp. [31]

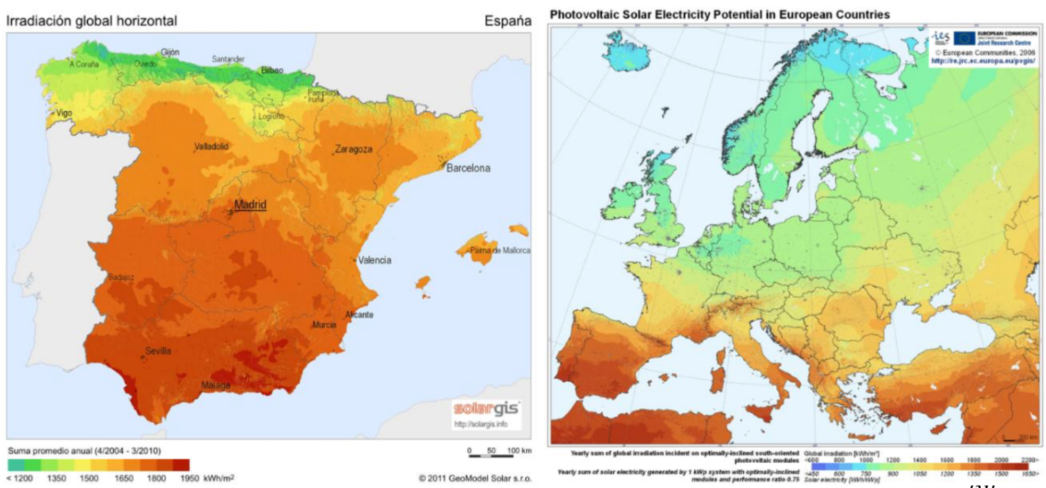

Figure 2.5. Values for annual solar radiation in Asturias are similar to the ones obtained in Germany [31]

The main reason why solar energy has been rejected so far in Asturias is because in the rest of Spain, solar energy potential is much higher and installations costs are lower. However, persisting cost trends, improving on efficiency of solar photovoltaic and collectors, and increasing the prices of fossil fuels, it would make it a real and competitive alternative. On the other hand, the main drawback that solar energy will have to face is the Spanish regulations.

For the Principality of Asturias, FAEN has developed several studies, among them "Solar Bulletin of the Principality of Asturias 2007-2010" and the "Asturias Solar Map", collecting different solar values during several years. Thus, FAEN has created a solar map, figure 2.6, making a division between climatic zones to facilitate the energy study with the solar panels specific to each zone. The majority of municipalities in Asturias belong to zone I (radiation lower to 3800 Wh/m^2), according to the criterion established by the Technical Building Code. This criterion is regarding the global average daily solar radiation. Nevertheless, some minority areas belong to zone II (radiation greater of equal to 3800 Wh/m^2). [5], [14]

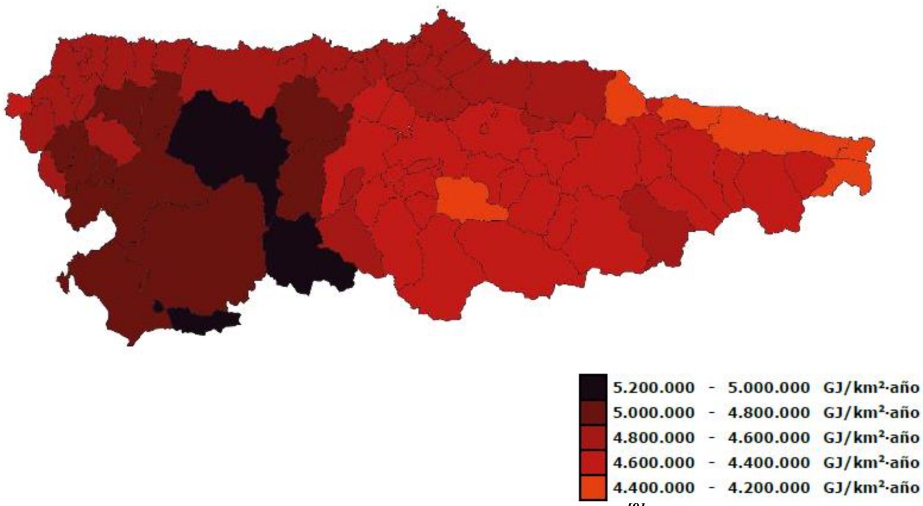

Figure 2.6. Asturias annual solar radiation map created by FAEN [9]

One of the alternatives for distributed generation, and which will be deepened in this project, is the use of photovoltaic technology. This will imply taking advantage of the roofs of single-family houses to produce electricity that can be poured into the grid or stored in batteries. From the industrial point of view, photovoltaic energy can have a great future in the small industry, incorporating this technology in the roofs of industrial buildings. However, the large-scale development is currently limited by legal restrictions in force in Spain.

⇒ <u>*Biomass*</u>

Given the climatic conditions of the region, which favor the development of crops and farmsteads, biomass could be a short-term energy alternative. On the other hand, the numerous environmental restrictions that Asturias has, do not support their large-scale development.

Biomass production involves several advantages, both environmental and economical. From the forestry point of view, means turning a waste into a possible resource, that is, giving an economic value to something that previously did not have it. Among the advantages of using biomass are [14]:

- It is a regional fuel and therefore does not depend on fluctuations in international markets. It also reduces energy dependence and is adaptable.
- It is produced in the rural environment, contributing to generate employment and favoring the movement of population to rural areas. Exploitation of forest biomass in a planned way contributes to the prevention of fires and against the appearance of pests.
- It contributes positively to greenhouse effect, since the balance of CO_2 emissions is zero, fulfilling the environmental commitments.

However, the development of biomass has not been as expected in the last decades. The main difficulties for implementation as an energy source has been:

- Despite having a mature processing technology, it is an unconstrained market due to the uncertainty about the biomass supply, since the availability is not assured.
- It is a very dispersed resource, both in terms of raw material and in processing. The complicated Asturias orography makes the costs of extraction and transport higher.
- The new Spanish regulatory framework establishes, a priori, insufficient regulatory premiums for projects development.

As an alternative to electricity production in Asturias, the potential of energy hybridization should be considered. It is a trend that is being developed lately at a global level. Highlighting hybrid wind-photovoltaic systems, or those combining a renewable resource with the support of a diesel engine. [9]

2.2- Distributed generation or distributed energy resources (DER)

The traditional electricity generation model is that electricity is generated in large centralized facilities, such as nuclear power plants, thermal power plants or hydropower plants. In short, modern electrical systems, until a few years ago, are made up of huge power plants and large transmission and distribution networks to reduce production and distribution costs. The location of these plants is determined by economic, security, logistical or environmental factors, among others, which cause that energy is consumed far from where it is generated. [8]

In the last years, a new concept of generation has taken force in the electrical system that by its intrinsic characteristics is installed mainly in the distribution networks, known as *Distributed Generation* (DG), being understood as such that small electric power generation and next to the consumer.

❖ *The evolution of the current electrical system: Smart Grids*

With the objectives of reducing environmental impact, improving safety in the supply of raw materials (mainly oil and natural gas) and achieving sustainability of energy systems, in 2008 new targets were set in Europe. Energy policy towards the year 2020, commonly known as the 20/20/20 Horizon 2020, which are:

- Reduction of greenhouse gas emissions by 20% compared to 1990.
- Renewable energies will produce 20% of the total energy consumed.
- Improved energy efficiency by reducing total energy consumption by 20%.

The integration of new technologies that help achieve the 20/20/20 objectives is a process widely known as Smart Grids. Smart Grids are electrical grids that allow the integration of distributed energy resources (DER: Distributed Energy Resources) efficiently, optimizing service quality at the lowest price. The DERs are: [8]

- Distributed generation
- Active participation in the demand
- Electric vehicle
- Decentralized storage

It is vital to understand that Smart Grids are not something new, neither a revolution nor anything that implies getting rid of the current system. Smart Grids are a continuous evolution of the current electrical system that will allow the integration of the distributed energy resources improving the quality, efficiency and sustainability of the service and electric products.

However, the success of this process is dependent on the technological development of the technology itself and the appropriate regulatory framework.

❖ *The Spanish inconsistency about Distributed Generation*

During years, Spain has lived from the building sector. This has led Spain to build a very extensive electricity network, especially in distribution, created to supply future exponential demand projections. However, what had happened, has been quite the opposite, due to the economic crisis. These expensive networks were wasted and power companies needed to recover the investment in some way. This is one of the key points that will facilitate understanding the why of the policies and regulations in the electric sector that have been implanted in Spain. When in most of the developed countries measures are being promoted to favor the development and integration renewable energies for distributed generation, more specifically the self-consumption regime, in Spain the opposite has been done. [18], [20] The most popular and accepted European measures, as opposed to those foreseen for Spain, according to the draft of the Royal Decree of Self-consumption proposed in June of the year 2015 are, according to the article "Ten differences between self-consumption in Spain and Rest of Europe ":

- Generate economic or other incentives to enable consumers to empower themselves in the electricity sector by saving, undertaking demand management measures or self-producing their energy. In Spain, a country with high solar radiation, high electricity prices and low price of producing photovoltaic energy, would not require any premium or incentive to self-consumption, just avoiding all kinds of obstacles. The current Government projects totally unjustifiably and disproportionately taxes for self-consumed electricity with higher charges than the energy coming from the electricity grid. In Germany, energy discharged to the grid by a self-consumption facility gets a premium if it comes from an installation lower than 100 kWp. [20]

- No to taxes or discriminatory charges on self-consumed energy. It does not make sense to charge fees and taxes to a measure of energy efficiency that is also an exercise of the universal right to the sun and that in it does not generate additional costs to the system but quite the opposite. In Italy facilities, less than 20 kW do not pay any type of charge or tax. In Portugal, they are exempt until self-consumption reaches 3% of the total installed capacity in the country. In Germany, they pay charges but receive a higher premium. In Spain, on the contrary, the Government wants to charge the energy produced that does not even reach the electricity grid with rates higher than those applied to the electricity that the consumer would buy from the grid. [20]

- The right to receive at least the market price for electricity discharged into the grid. Normally the facilities can compensate in net balance the energy poured and the acquired of the network and to sell to the network its surpluses at the price of the pool. There are even cases in which a premium is paid for electricity discharged into the grid, as in the case of Germany, Croatia or Denmark. [20]

2.3- ASES system description

A new technology is being developed to cover the tap water and heating needs. This system may be implemented into buildings, making them more efficient. The system is called ASES, Active Solar Energy Storage. This new method is optimized for seasonal storage of solar heat. During summer, solar heat is absorbed by solar collectors on the roof as is illustrated in figure 2.7; the excess heat is accumulated in a seasonal storage underneath the building. Heat is retrieved from the storage during cold seasons using a heat pump. Slings are placed at the bottom of the geothermal storage. [25]

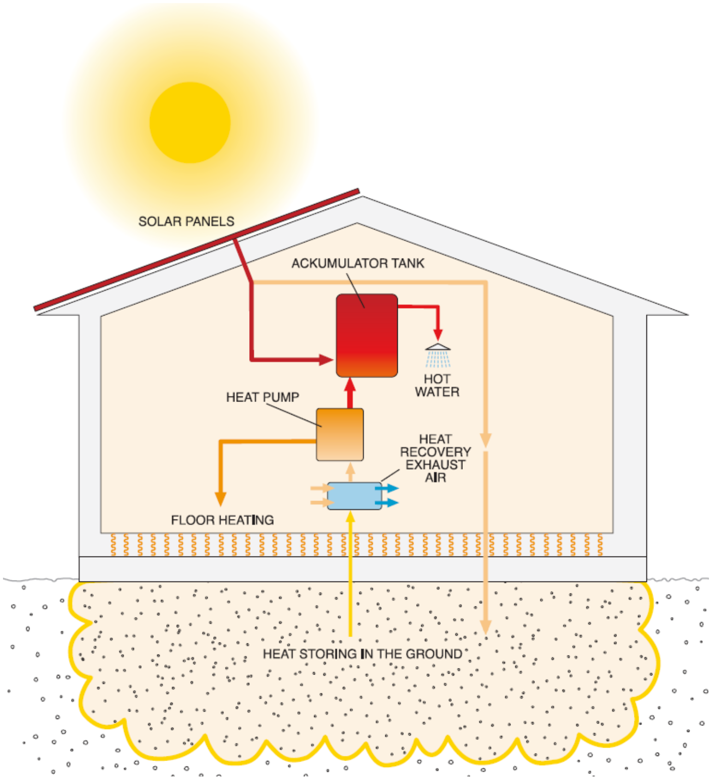

Figure 2.7. Scheme of ASES system. Excess solar heat collected by solar collectors will be store in the geothermal storage [25]

ASES is a heating system that is used to heat both hot water and radiators/floor heating in a building. The primary energy source for the system is solar heat from solar collectors. Some of the solar heat is used to heat up tap water in a water storage tank. The remaining solar heat that is received will be stored in a geothermal storage positioned below the building. Here the solar heat will be seasonally stored. A heat pump is used to retrieve heat from the geothermal storage when heat from the solar collectors is insufficient to meet the building demand.

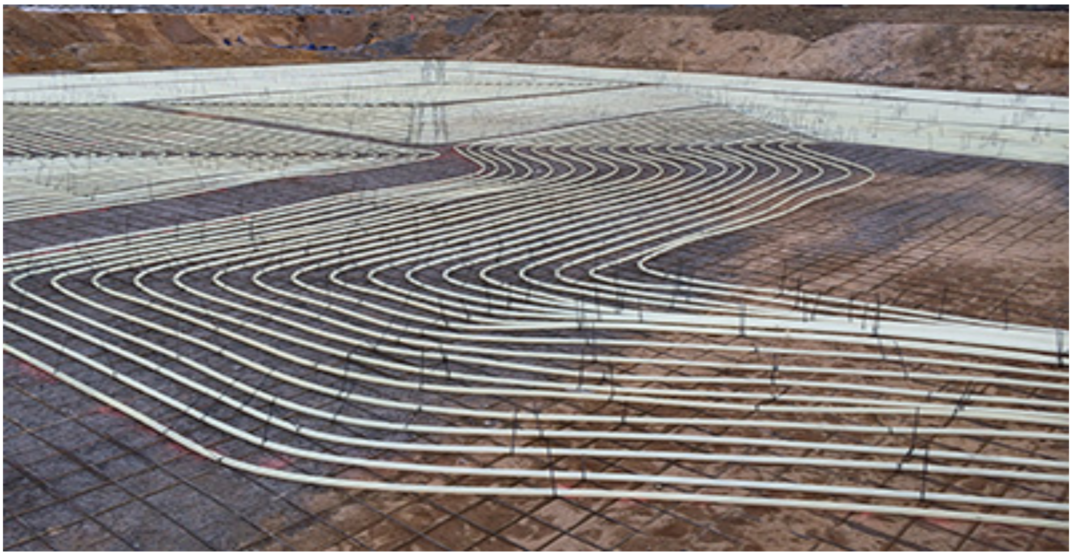

Figure 2.8. Slings are placed at the bottom of the storage and are connected to both heat pump and solar collectors [25]

The geothermal storage below the building is constructed from stone powder with high amount of silt and the surrounding ground. Stone powder has high specific heat capacity to be able to store large amounts of heat within a specific volume. A high amount of silt is needed to decrease the amount of air in the storage, increasing the heat transfer rate. Slings are mounted at the bottom of the stone powder layer as can be seen in figure 2.8. The slings are connected to both the heat pump and solar collectors and will be able both to feed heat to the storage as well as feeding it to the heat pump. Heat will conduct from the slings to stone powder and surrounding ground when the solar radiation to the collectors is high. When the heating demand is greater than the supply, the heat pump will retrieve it from the storage and slings. [25]

A solar collector is designed to absorb incoming solar radiation as heat. This is done by carefully choosing color and material of the solar collector absorber plate. An aluminum plate makes an efficient heat transfer and covered in a black coating to absorb the sunlight. Heat is transferred from absorber to pipes by conduction. The pipes contain a continuously flowing fluid that transports the heat away. To minimize heat loss to the surrounding air, the back and sides of the solar collector are well insulated. The collector also has a transparent cover (usually glass) to reduce thermal losses and to protect from damage [7]. This is the design of a flat plate solar collector and is shown in figure 2.9. Although it would vary over the year, heat losses can be estimated precisely because varies with temperature difference. That is, when ambient temperature is higher, efficiency of solar collectors is higher than when temperatures are lower. This will introduce some errors but will be enough to make initial calculations for the storage.

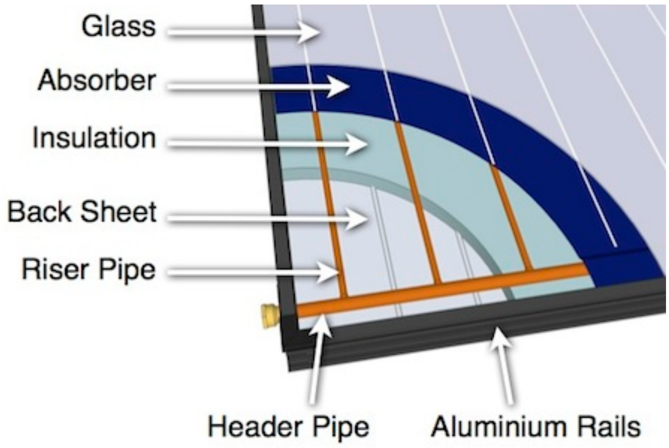

Figure 2.9. Scheme of components in a solar flat-plate collector [7]

To distribute solar heat different systems can be used: radiant floor, hot water baseboards or radiators or a central forced-air system. When working with ASES, radiant floor is the optimal system where solar-heated liquid circulates through pipes embedded in a thin concrete slab floor, which then radiates heat to the room.

2.4- Solar energy

Earth rotates around the sun in an elliptical orbit with a mean radius of $149.73 \cdot 10^{26}$ m. Every revolution is equal to one year. Earth also rotates around its own axis and every revolution is equal to 24 hours. This axis is named polar axis and it is tilted 23.45˚ relative to the normal for earth's elliptical orbit around the sun. The equator plane is perpendicular to the polar axis. Radiation flux from the sun is $3.85 \cdot 10^{26}$ W. [19]

To calculate to solar radiation first, the declination angle, δ, is calculated. Declination angle is defined as the angle of a sun vector relative to the equator

$$\delta = 23.45 \cdot \sin\left(360 \cdot \frac{284 + n}{365}\right)$$

$$-23.45° \leq \delta \leq 23.45°$$

where n is equal to day number and January 1st has n=1. All calculations are made for the mean day number of each month.

The solar radiation relative to a horizontal surface, zenith angle, θ_z, is calculated for every hour. If Zenith angle is larger than 90˚ there will be no solar radiation on the horizontal surface. Zenith angle is calculated as

$$\cos\theta_Z = \cos\varphi \cdot \cos\delta \cdot \cos\omega + \sin\varphi \cdot \sin\delta$$

where φ is equal to the latitude and ω is equal to the hour angle described below.

If the surface is tilted instead of horizontal, the surface orientation needs to be considered. The surface orientation can be described with the tilt of the surface together with the azimuth angle, ϒ. It is defined as the angle between the projection of the surface normal and south direction.

The angle of incidence, θ, defined as solar radiation relative to a tilted surface can be calculated as

$$\cos\theta = \sin\delta \cdot \sin\varphi \cdot \cos\beta - \sin\delta \cdot \cos\varphi \cdot \sin\beta \cdot \cos\gamma + \cos\delta \cdot \cos\varphi \cdot \cos\beta \cdot \cos\omega + \cos\delta \cdot \sin\varphi \cdot \sin\beta \cdot \cos\gamma \cdot \cos\omega + \cos\delta \cdot \sin\beta \cdot \sin\gamma \cdot \sin\omega$$

Also, here the hour angle, ω is included in the calculation. Hour angle is calculated as

$$\omega = 15 \cdot (t - 12)$$
$$-180° \leq \omega \leq 180°$$

where Solar time, t, is calculated as

$$t = standard\_time + \frac{4(L_{loc} - L_{st}) + E}{60}$$

where L_{loc} is equal to local longitude, L_{st} is equal to standard longitude and E is equal to a time correction term

$$E = 229.2 \cdot (0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin 2B)$$

where B is calculated as

$$B = 360\frac{n-1}{365}$$

The solar constant, G_{SC}, is defined as solar radiation from the sun to the atmosphere of earth is calculated to 1368 W/m^2 when earth is at mean distance from the sun.

Solar radiation at a horizontal surface, $G_{0,n}$, depends on which day of the year it is and is calculated in the following way:

$$G_{0,n} = G_{SC} \cdot \left(1 + 0.033 \cdot \cos\left(360 \cdot \frac{n}{365}\right)\right)$$

Solar radiation on a horizontal surface, not directed towards the sun, is calculated using the zenith angle as

$$I_0 = G_{0,n} \cdot \cos\theta_Z$$

Since the atmosphere usually is partly cloudy, this needs to be considered. Therefore, a clearness index, K_t is defined by

$$K_t = 0.803 - \frac{(0.916 \cdot C + 0.34)^2 - 0.34^2}{1.832}$$

where C is equal to mean cloudiness for each month.

The solar radiation can be divided into beam radiation, I_b, and diffuse radiation, I_d, where beam radiation is defined as radiation directly on the ground without any change in direction and diffuse radiation is defined as radiation reaching the ground after direction change due to particles in the atmosphere.

$$I = I_b + I_d$$

The diffuse radiation is calculated as

$$\frac{I_d}{I} = \begin{Bmatrix} for\ K_t < 0.22 & = 1.0 - 0.09 \cdot K_t \\ for\ 0.22 \le K_t \le 0.8 & = 0.9511 - 0.1604 \cdot K_t + 4.388 \cdot {K_t}^2 - 16.638 \cdot {K_t}^3 + 12.336 \cdot {K_t}^4 \\ for\ K_t > 0.8 & = 0.165 \end{Bmatrix}$$

and the beam radiation is calculated as

$$I_d = I - I_b$$

Finally, the total solar radiation on a tilted surface can be calculated as

$$I_T = R_b \cdot I_b + R_d \cdot I_d + R_r \cdot \rho_g \cdot I$$

where ρ_g, Albedo, is equal to the ground reflection. Beam component, R_b, is defined as a relation between radiation incident on a tilted surface and radiation on a horizontal plane

$$R_b = \frac{\cos\theta}{\cos\theta_z}$$

and diffuse component, R_d, is defined as the view factor of hemispherical isotropic radiation on a tilted surface

$$R_d = \frac{1 + \cos\beta}{2}$$

The reflected component, R_r, is defined as the view factor of isotropic ground radiation on a tilted surface

$$R_r = \frac{1 - \cos\beta}{2}$$

Input data for location Gijón in Spain is presented in table 2.5.

Input data, Gijón, Spain		
Longitude [˚]		-5
Latitude [˚]		43
Earth albedo	Jan - Dec	0.25
Mean cloudiness [%]	Jan – May, Oct - Dec	65
	Jun - Aug	55

Table 2.5. Input parameters for Solar radiation calculations [9]

2.5- Heat and electricity demand of a building

The building requires heat to both tap water and radiators. Tap water consumption is almost constant during a year but heating will vary from winter to summer. During winter, there are high heat demand peaks during cold days, especially during February. According to DB-HE4 [5], tap water consumption is estimated to 28 l/day for residents. Using ASES, up to 75% of the tap water heating is collected directly from the solar collectors. The radiator heating depends on several factors. The primary factor is the outdoor temperature. Other parameters to consider are:

- Thermal resistance of the building envelope.
- Indoor temperature.
- Visiting hours of the residents.
- Airing hours of the building.
- Additional heating systems (and ventilation system).

All the parameters above are specific to every building, but DB-HE4 has standardization of some of the values and other must be simulated.

The simulated building is not considered to have any cooling system, since the outdoor temperature does not reach enough values to need a cooling. The thermal resistance of a building envelope is called a U-value and is one of the key figures of a building. The simulated building has a U-value 0.24 which correspond to good thermal resistance of the building.

The system will need a heat pump to convert low tempered fluid to a high temperature gas using a compressor. The compressor consumes electricity. A key figure for heat pumps concerning the electricity consumption against the total energy that is emitted on the hot side of the heat pump is called seasonal coefficient of performance, COP, and is calculated as

$$COP = \frac{Heat\ demand\ of\ building}{Electricity\ to\ heat\ pump}$$

Using less electricity will bring a higher COP value. The heat pump working with ASES storage has a COP of 4.85. [30]

2.6- Net energy metering system (NEM)

Regarding different alternatives for generating and consuming energy, only one of them is considered within this project: net energy metering, considering that the photovoltaic installation is connected to the distribution grid.

This form of generation allows generating all the energy that the installation is capable, without having to regulate the production according to the consumption and without the need to have a system of energy storage.

NEM is a system of energy balance compensation that allows pouring the excess electricity produced to the grid by a system of self-consumption. In this way, the surplus of energy would be consumed at another time where the PV production is not enough, acting the distribution grid as an energy accumulator. Within this system, savings for the consumer are maximizing since it allows managing its production curve with its demand curve. [24]

Figure 2.10 shows a comparison scheme between a self-consumption system and a net energy metering one. Differences between both systems are easily observed.

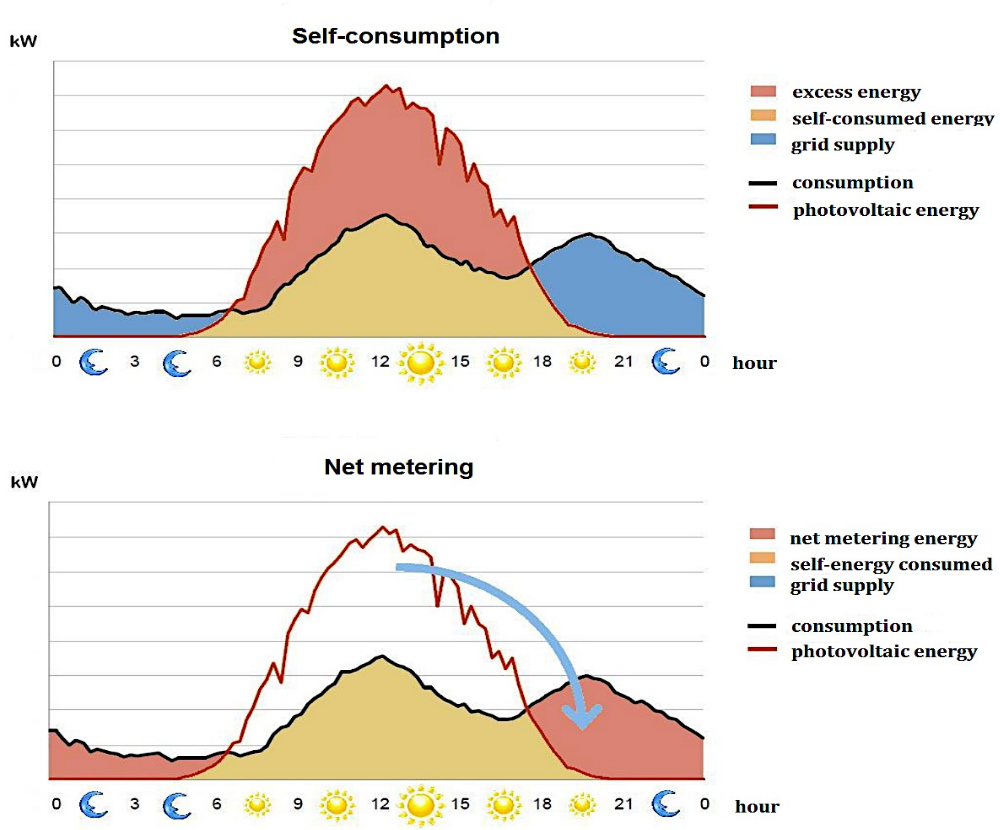

Figure 2.10. Comparison between self-consumption and net energy metering systems [24]

2.7- Simulation in CFD

With CFD Fluent software it is possible to design a desired geometry of the storage. The dimensions and transient simulations will indicate the temperature distribution in the geothermal storage. This will provide information of how much energy passes through the slings as well as the energy losses.

Geometry of the storage is sketched as in figure 2.11, including the insulation layer, the storage and the ground. Everything is generated into a mesh. A mesh divides each zone of the geometry into small calculation boxes: a finer mesh will provide a higher precision. In the interface of the slings it will be preferable to insert a refinement to have a detailed area where the heat transfer is going to be measured. [2]

All the thermal properties of the materials that are used are set up: air, clay, stone powder and mineral wool. Boundary conditions are set for both areas and interface lines. The boundary conditions are specific temperatures, thermal properties and conduction properties. Due to the symmetry of the geometry only half of the storage is designed which makes the simulations faster. [1]

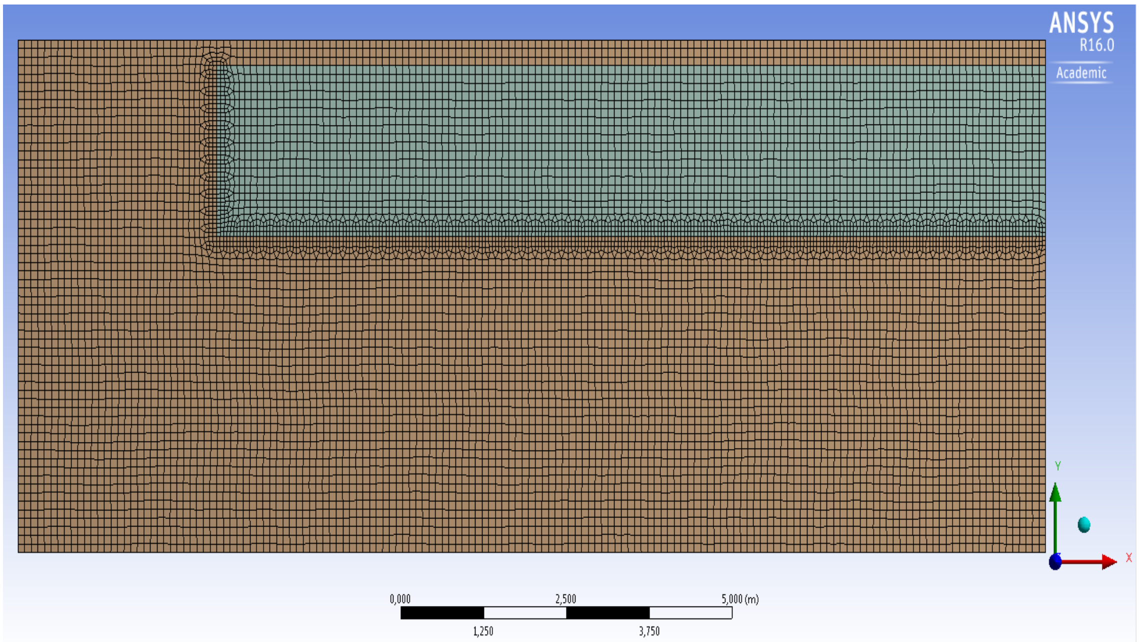

Figure 2.11. The storage sketch is converted into a mesh for providing a higher precision when running transient simulations.

3. Method

3.1- Energy Building Demand

To determine the number of solar collectors, PV panels and storage dimensions, the energy demand of the house is needed. There exist several possibilities to calculate the energy needs. In this project, energy invoices of a single-family house during last three years were collected. These invoices reflect the energy consumption in periods of two months.

The house under study cannot be an average house for future studies. It has an available surface of 240 m^2 divided in two floors composed with five bedrooms and four bathrooms; a basement and a garage. The total roof's surface is approximately 170 m^2. However, since solar panels will be placed only in the South-faced area, the available surface for installing is 60-70 m^2. Elements that will contribute to increase the energy consumption over the average values are:

- Two fridges and two freezers.
- A 32m^2 non-acclimatized swimming pool.
- Exterior lighting
- A dishwasher and a dryer

Since the consumption each year may vary due to weather conditions and other factors, the average between last three years have been used. However, in this project it will be considered monthly consumption. Therefore, it was considered an energy factor 'k' to split the average values obtained in the bi-monthly periods into monthly ones. To do so, February was assumed to be the month with higher heating needs due to it was the month with lower temperatures according to data given by Meteogijon [36]. From July to October there are no heating needs. Average annual heating consumption is presented in figure 3.1.

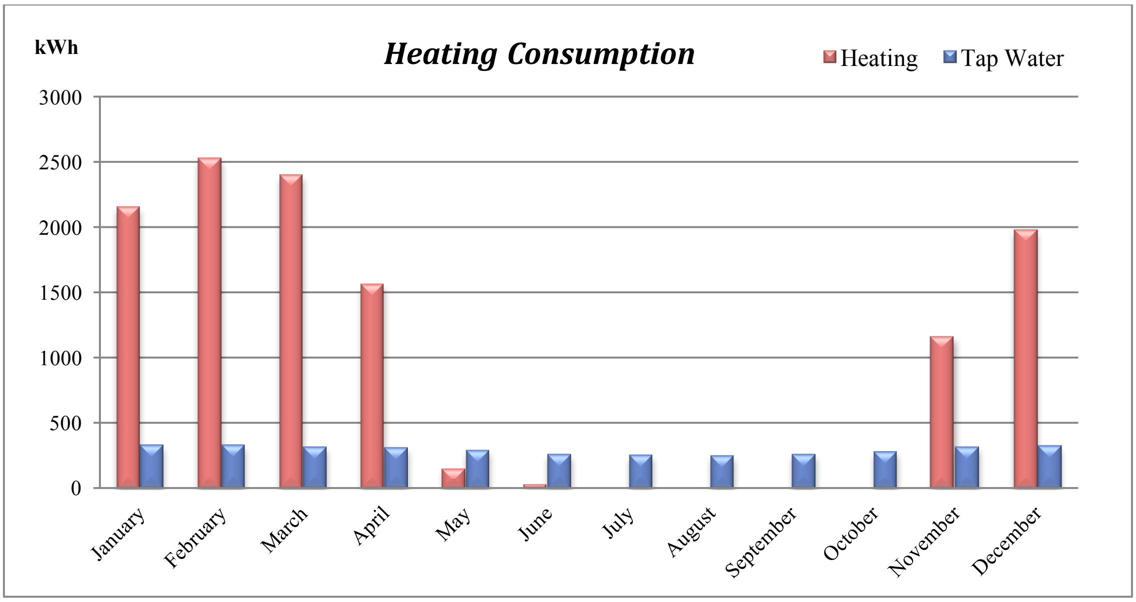

Figure 3.1 - Distribution heat and tap water over a year for the single-family house

Regarding the electricity consumption, the same procedure was applied as for heating. February was the period with higher consumption while July and August have the lower electricity needs as can be seen in figure 3.2.

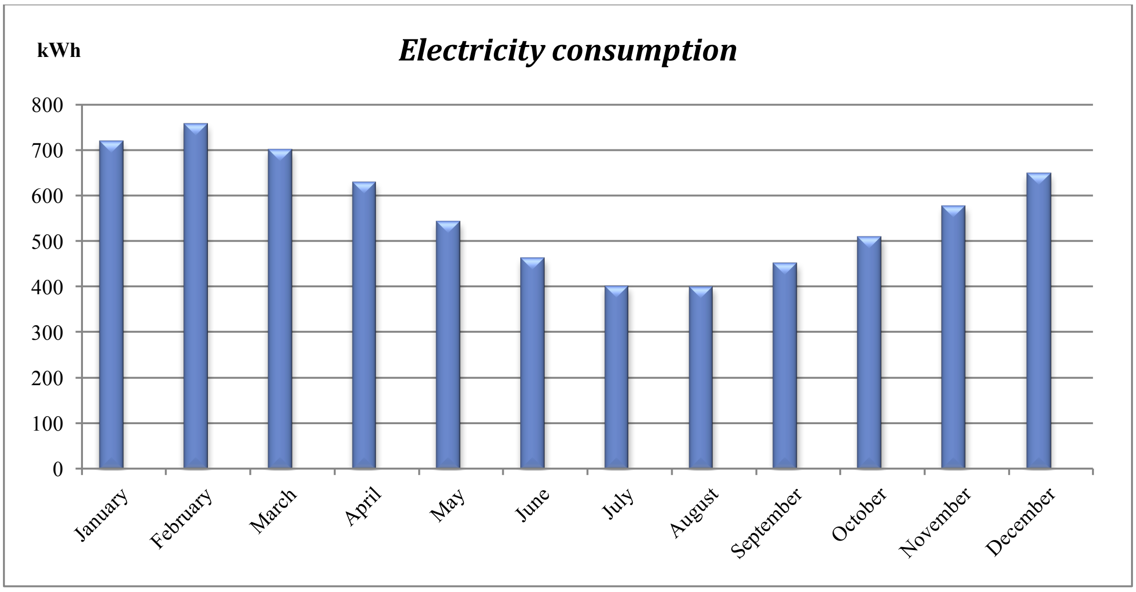

Figure 3.2 - Distribution electricity consumption in a single-family house over a year

It should be considered that the values obtained are from a singular single-family house and it cannot be extrapolated to general point of view. That is because a multiple family house might have higher consumption so then, the system should be re-designed. Nevertheless, it can represent the consumption of a wide number of dwellings like the one considered in the region, considering the same surface, similar electrical devices and residents.

For simplification of study, the hourly consumption distribution throughout the day has been constant for all the days of the week and for all months of the year. Assuming this hypothesis, it is known that an error is being made in this aspect. However, it has been preceded to realize a unique hourly consumption pattern so that the model in this way facilitates the study, which is presented in figures 3.3 and 3.4. [20]

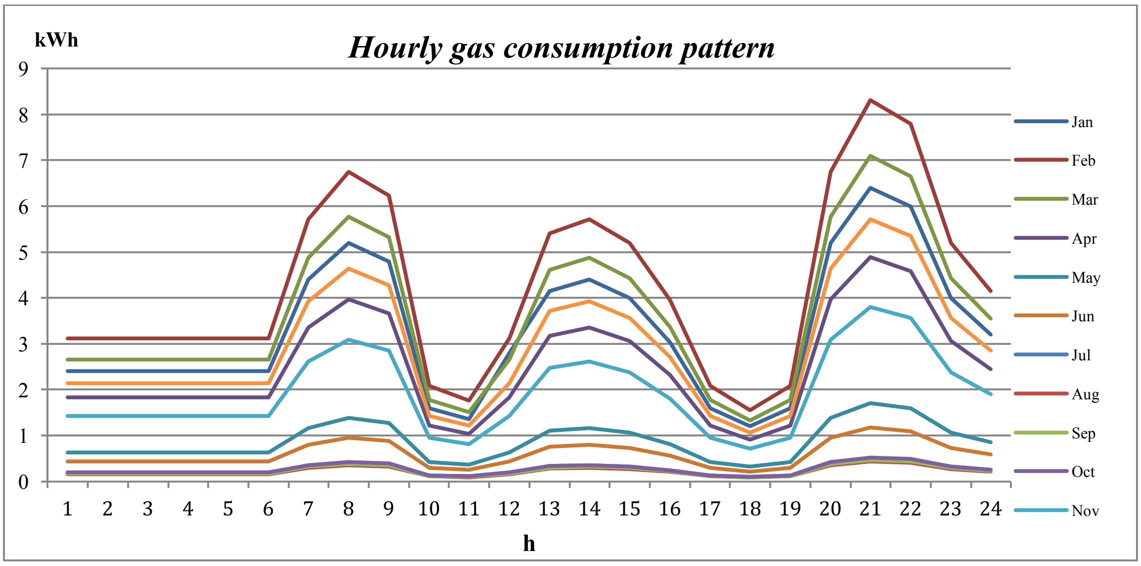

Figure 3.3 - Distribution of hourly heating demand through a single day over a year

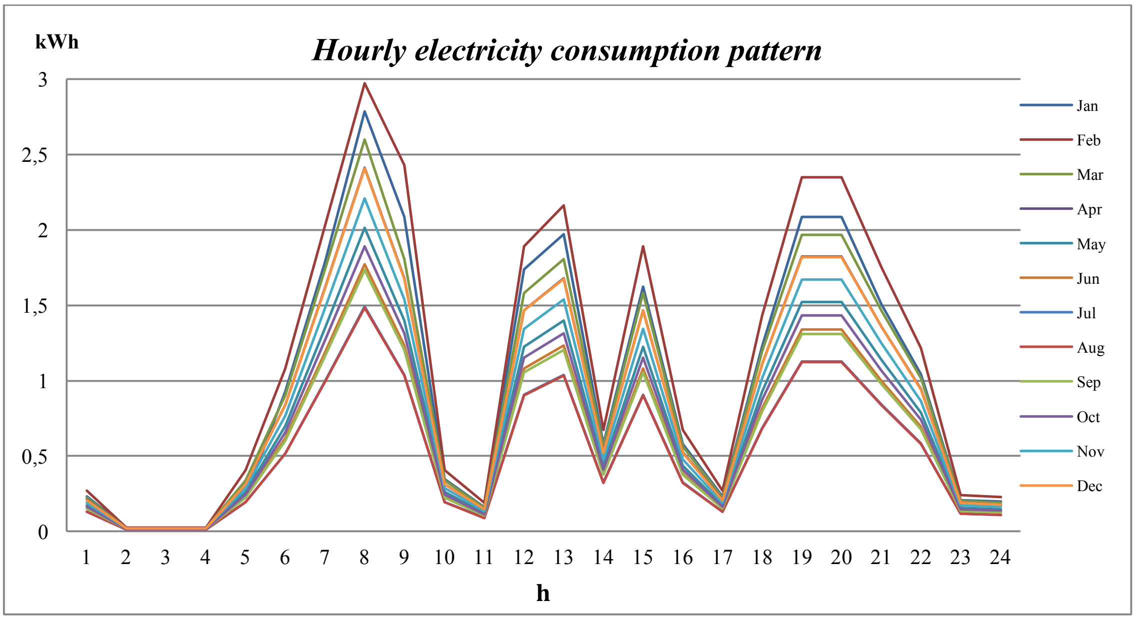

Figure 3.4 - Distribution of hourly electricity consumption through a single day over a year

3.2- Modeling in CFD

A building is designed to be the basic model for the case in Gijón, Spain. The model will be represented as a cross section of the building with a width of 25m and 3m deep creating a 2D-model.

A relationship between heat demand of the building and solar input is set up. Solar energy will be found using different sources. The relation between heat input and heat output will result in finding the number of solar collectors and the amount of energy that has to pass through the storage after installation. [33]

The storage behavior and capacity will be simulated using CFD Fluent software. The initial temperature of the storage will be the undisturbed ground temperature. By using a specific sling temperature in the storage between day and night it will be possible to predict the behavior during a month. The same method is used to predict the behavior for every month of the year. For each case heat transfer from slings are logged. From this the behavior of the storage is set. The result from the two similar models is compared to see if the storage design is optimized. [1]

To obtain good results, a proper model with its thermal properties is required. For this purpose, is important to know the temperatures in the storage vary during the day and during the night for each month, the air temperature and the thermal properties of the materials used as the thermal conductivity and the specific heat capacity for the stone powder, the clay and the mineral wool that will be used as an isolation material.

To begin modeling the thermal storage in CFD Fluent Software, initial temperatures for the storage, slings and air will be needed for each month. In table 3.1, slings temperatures for each month are presented considering average values given by Norconsult AB. The air temperature is taken from the database given by Meteogijon [36], and is represented in figure 3.5. In order to get the initial temperature in the storage, a non-linear distribution will be considered. Therefore, after running simulations of the previous month, several points distributed arbitrarily around the storage are considered to obtain their temperatures. Then, by averaging the difference temperatures between those points, and extrapolating the result for the number of days of the correspondent month, an estimation for the initial storage temperature in the following month is known.

Slings Temperature

Month	Day [K]	Night [K]	Month	Day [K]	Night [K]
January	293	280	July	318	298
February	293	280	August	318	298
March	298	285	September	308	288
April	303	286	October	303	286
May	308	288	November	298	285
June	318	298	December	293	280

Table 3.1 - Monthly slings temperatures considered for day and night for running simulations in CFD

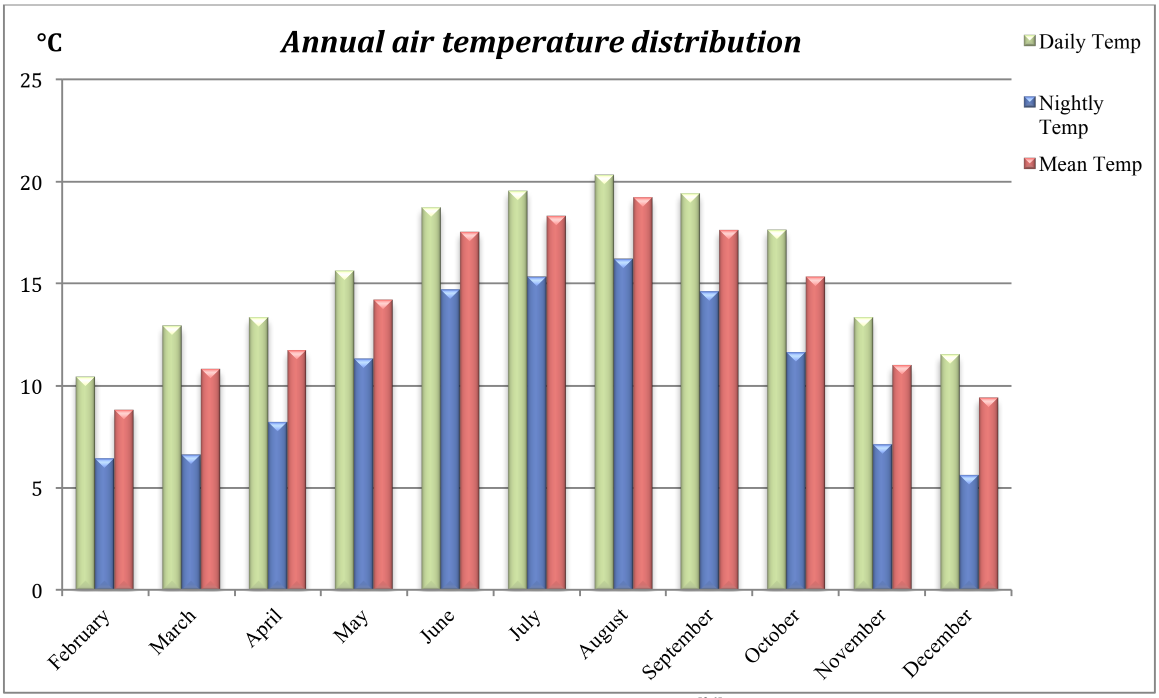

Figure 3.5 - Annual air temperatures distribution in Gijón during 2016 [36]

However, to start with the first month of simulation, August was considered for being the month with higher temperatures and no heating needs and the initial temperature of the storage was assumed by considering several parameters to be 293-K. To get accurate results, each month simulated is composed of 30 simulations, 15 days and 15 nights.

By knowing how much energy passes through the slings during each period along the days and nights and by knowing the heat demand of the house, estimation of how much the storage is charged can be done. This means that it will be known if the storage reaches the maximum capacity, then no more heat will be put down to the storage. In addition, the simulation will reflect how much energy should be put inside the storage.

3.3- Solar radiation

The Spanish Basic Document for Energy Saving (DB-HE) indicates the boundaries between homogeneous climatic zones for the requirement. The zones have been defined taking into account the global annual average solar radiation on the horizontal surface (H), taking the intervals that are related for each of the zones. Values are represented in table 3.2. However, this can only be an indicator since are annual average values. Gijón belongs to climate zone I. [5]

Climatic zone	MJ/m^2	kWh/m^2
I	H < 13,7	H < 3,8
II	13,7 ≤ H < 15,1	3,8 ≤ H <4,2
III	15,1 ≤ H < 16,6	4,2 ≤ H < 4,6
IV	16,6 ≤ H < 18,0	4,6 ≤ H < 5,0
V	H ≥ 18,0	H ≥ 5,0

Table 3.2 - Annual average solar radiation values on a horizontal surface in function of the climatic zones in Spain [5]

In order to calculate the energy that solar panels would produce, it is necessary to know the incident solar radiation on them. Several possibilities are available to solve this issue. In section 2.4, mathematical equations were described where several parameters might be considered such as the earth albedo, cloudiness, day hours, panels tilt, etc. Apart from considering the values obtained mathematically, two more sources were contemplated. Monthly solar radiation values have been obtained from Polysun software and from the PVGIS-CMSAF European database.

The solar radiation values that finally were used throughout this project come from averaging the results obtained from the three different data sources. Therefore, figure 3.6, reflects the different incident solar radiation values obtained over a solar panel with 20° inclination.

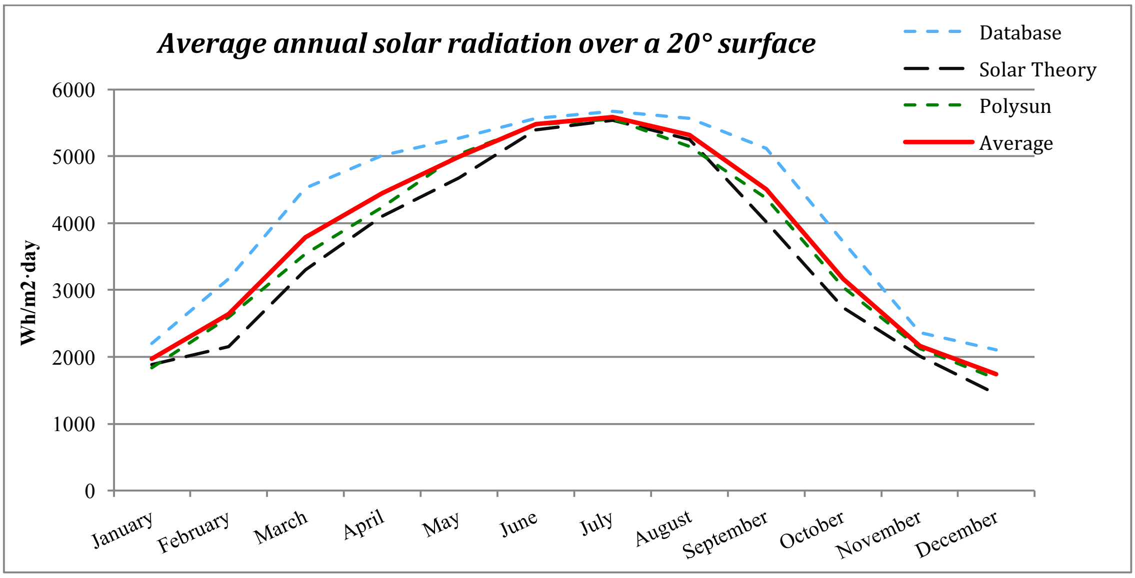

Figure 3.6 - Distribution of solar radiation values over a 20° surface from different sources

3.4- PV installation

As with solar thermal systems for domestic hot water, a minimum contribution of electrical energy obtained by systems for capturing and photovoltaic processes transforming solar energy is established.

A grid-connected photovoltaic solar system consists of a set of components responsible for performing the functions of capturing solar radiation, generating electricity as a direct current and adapting it to the characteristics that make it usable by the consumers connected to the AC distribution grid. These types of photovoltaic installations work in parallel with the rest of the generation systems that supply to the distribution network. [8]

The systems that make up the photovoltaic solar installation connected to the grid are the following:

a) Photovoltaic generator system, composed of modules, which in turn contain a set of semiconductor elements, connected to each other, called cells, and which transform solar energy into electrical energy;
b) An inverter that transforms the direct current produced by the modules into alternating current of the same characteristics as that of the electric network;
c) Set of protections, safety, and maneuvering, measuring and auxiliary elements.

The solar PV installation will be composed by a total of 16 photovoltaic modules having a total surface around 30-32 m^2. Solar panels will be placed in the single-family house roof, with south orientation and a total inclination of 20°. The electricity produced would be put in the dwelling low voltage network.

In order to make the photovoltaic analysis it has been considered that the installation is done on the house oriented to the South and free of shadows. However, losses due to temperature factors (8.3%), electrical losses (7%) and losses of the whole system including possible shadows (18%) have been considered by making a comparison of the several parameters in different solar modules. Moreover, to obtain an average value taking into account possible errors, photovoltaic energy values from the Spanish simulation software Censol 5.0 are taken. [20]

The solar PV system designed would be defined by 16 panels of 240 Wp each one which will deliver a total peak power around 3840 W when working on optimal conditions. The main characteristics of the photovoltaic panels are recollected in table 3.3. The module characteristics that are presented do not correspond to any product. Principal features have been defined after conducting a market research on different current possibilities, comparing characteristics of monocrystalline and polycrystalline modules. Thus, it has concluded in a model whose characteristics are intermediate between the different technologies. This makes possible to realize a general idea of the photovoltaic resource.

Photovoltaic panel	
Length [mm]	1825
Width [mm]	1030
Surface [m2]	1.88
Peak Power [Wp]	240
Price [€]	307
Price ratio [€/W]	1
Power ratio [W/m2]	170
Efficiency [%]	16.1

Table 3.3 - Average photovoltaic solar panel characteristics that are available in the market

However, main difference between monocrystalline and polycrystalline modules is that the former ones have a better efficiency in the solar energy transformation into electrical energy (16.5% versus 15%). On the other hand, polycrystalline panels have lower cost, close to 0.9 €/Wp (against 1.03€/Wp for monocrystalline). [28]

Since this is a research project to obtain an initial estimation, the analysis of the rest of the installation elements is not subject of this project. Only the electrical performance for the panels, which will affect the overall performance of the system, needs to be considered. This factor is known as the *performance ratio* (PR). Although the PR calculation procedure is detailed in "Technical Specifications for Solar Photovoltaic Energy Installations" published by IDAE, its calculation is not considered in this project since this is not for a specific installation and all data required is not available. [20]

Moreover, it is necessary to consider other electronic devices, such as investors or micro inverters. Currently, these components have yielded efficiencies close to 94%, values that have been improving significantly in recent years.

For this purpose, a value for the performance ratio would be estimated according with the energy system considered. The NEM is the easiest installation since it does not require any electricity storage. Therefore, according to theoretical values, a value of 0.85 for the PR will be assumed [5]. However, for further work, values for performance ratio will vary for each month.

3.5- Solar heating installation

Active solar heating systems use solar energy to heat a fluid and then transfer the solar heat directly to the interior space or to a storage system for later use. If the solar system cannot provide adequate space heating, an auxiliary or back-up system provides the additional heat. That is why a heat pump is needed when designing an ASES system for the single-family house.

The solar thermal system will consist on 10 solar collectors placed on the single-family house's roof. The solar collectors will have a total absorber are close to 26m^2. Following the same conditions that were used for installing the PV panels, solar collectors will have an inclination of 20°. The main difference of the heating system with respect to the electrical one is that it will satisfy all the heating needs. Therefore, there is no need to connect the house to the external heating grid.

Three types of solar collectors are used in solar water heating systems: flat-plate collectors, integral collector-storage and tube solar collectors. Flat-plate collectors were chosen for this project. However, tube solar collectors would be another possibility increasing the total efficiency and so, reducing the number of solar collectors.

For the designing of flat-plate collectors a market research on different current possibilities was done as it was for the PV panels. Thus, by comparing characteristics of different types given by alternatives solar collectors manufactures, a model whose characteristics are in-between was chosen. This makes possible to gather a general idea of the solar thermal resource available in the region.

However, thermal losses occur in the solar collectors. The loss of energy from a collector, by convection, conduction and heat radiation, can be represented by a heat loss coefficient, the U_L-factor. The heat losses, Q_f, mainly depend on the difference in temperature between the absorber and the surroundings and can be written by

$$Q_f = U_l \cdot (T_a - T_u)$$

and the useful extracted energy, at stationary conditions, may be given by the following expression

$$Q_u = A \cdot [S - U_l \cdot (T_a - T_u)]$$

where S is the absorbed radiation in the absorber surface (W/m^2) and A is the collector area (m^2).

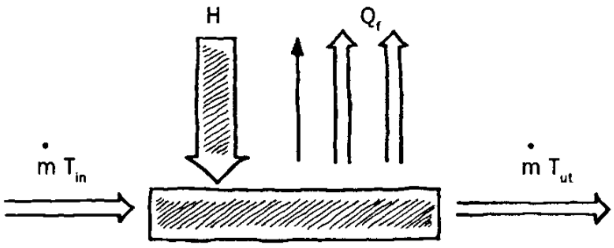

Figure 3.7 - Scheme of heat balance in a solar flat-plate collector

Instead, the useful energy, Q_u, is expressed as a function of the heat carrier temperature, T_V. To do so, a "collector heat removal factor", F, is introduced. It can be resembled to an efficiency coefficient for a heat exchanger, and tells how much heat that is transferred to the heat carrier, of what is maximally possible. F can be written as

$$F = \frac{Aqcuired\ useful\ energy}{\substack{Useful\ energy\ that\ would\ have\ been\ aquired \\ i \quad the\ brine\ would\ reach\ the\ absorbers\ temperature}}$$

Knowing the collector is irradiated by the solar radiation intensity H (W/m^2), the transmission coefficient, τ, which tells how large the part of the radiation that reaches the absorber is, and the absorptance, α, the absorbed radiation in the absorber surface is then written as

$$S = H \cdot \alpha \cdot \pi$$

The useful energy can now be expressed in the following way

$$Qu = A \cdot F \cdot [\tau\alpha \cdot H - Ul \cdot (Tv - Tu)]$$

and the outlet temperature from the collector can be expressed by the Hottel and Whillier model for flat-plate collectors

$$T_{out} = \frac{A \cdot F}{m \cdot c} [\tau\alpha \cdot H - U_l(T_v - T_u)] + T_{in}$$

where the values for T_{out} corresponds to the temperatures presented in table 3.1.

The heat loss coefficient, U_l, for glazed collectors is approximately 3-8 $W/m^2 \cdot K$. The collectors F-value usually varies between 0.85 and 0.99. The value considered in this project was 0.93. Thus, the instantaneous collector efficiency, η, is defined as the quotient between the useful energy, Q_u, and the solar radiation H, on the collector.

$$\eta = \frac{Qu}{H \cdot A}$$

Another way to obtained the flat-plate collector efficiency corresponds to the following expression given by UNE EN 12975 (Franhouer Institute) is

$$\eta = \eta_0 - k_1 \cdot \frac{(T_{in} - T_{amb})}{H} - k_2 \frac{(T_{in} - T_{amb})^2}{H}$$

where η_0 represents the optical efficient for the collectors and k_1 and k_2 are thermal losses coefficients. After calculating the collector's efficiency for each month, the annual average efficiency yields 38%.

The heat pump that is considered is a geothermal heat pump (GHP). The GHPs use the constant temperature of the earth as the exchange medium instead of the outside air temperature. The heat pump will need to be feed by electricity when solar collectors do not produce enough energy. This electricity will be given by one of the PV panels that are placed. The main characteristic that was to consider according to the heat pump was the nominal power. Thus, a 15-kW heat pump was considered to design the ASES system and retrieve the required energy from the storage. Table 3.4 indicates main characteristics for the flat-plate collector used.

Flat-plate collector	
Absorber area [m^2]	2.54
Overall area [m^2]	2.70
$\eta_{average}$ [%]	38
k_1 [W/m^2K]	3.162
k_2 [W/m^2K]	0.014
Price [€]	625
U_l [W/m^2K]	3.58

Table 3.4 - Characteristics of a generic flat-plate collector

Another important element of the heating system is the accumulator tank. It was considered following the same criteria for the solar collectors, by making a market research. The importance of an accumulator tank is to store the tap water that is consumed. A volume of 300 L for the tank was considered enough to store tap water.

4. Results and analysis

4.1- Storage temperature

The transient simulations of the geothermal storage presented a temperature gradient. In figure 4.1, temperature distribution in the storage is observed after simulating 15 days of a summer month, specifically, July. The interface between the ground and external air will produce another temperature gradient. Thermal losses from the storage and slings will decrease over the years, since the temperatures in the storage and ground will be stable as the surrounding ground becomes warmer.

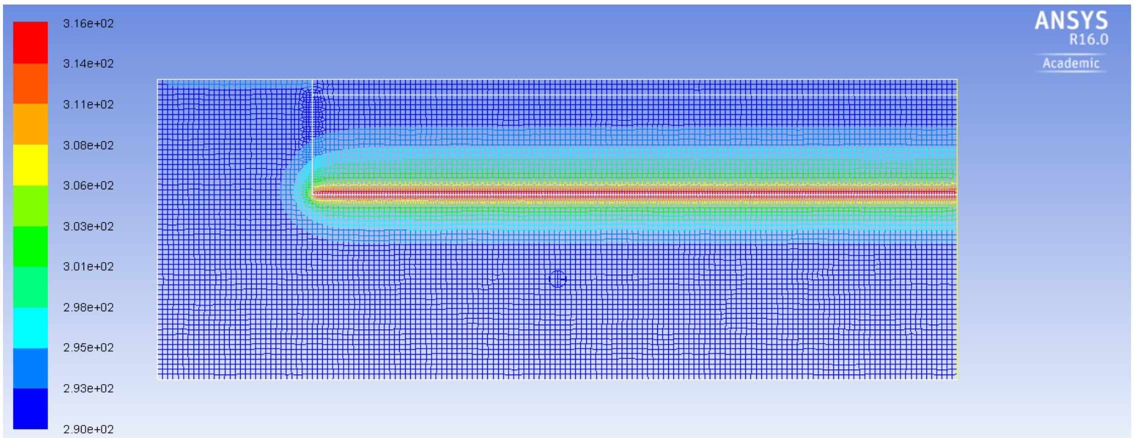

Figure 4.1 - Hot water through slings produces an increase in storage temperature. Simulated figure corresponds to 15^{th} day of July

During winter months, for instance figure 4.2 represents the simulation in January, due to a decrease in the ambient air, initial conditions will be lower than the ones in autumn (see figures in Appendix A). Daytime during winter season, slings temperatures are higher than the ground temperatures. On the other hand, when night reaches, slings temperatures decrease below the storage temperature. Therefore, since the storage is warmer, heat is transferred from storage to slings. This heat is later retrieved by means of a heat pump to the interior of the house.

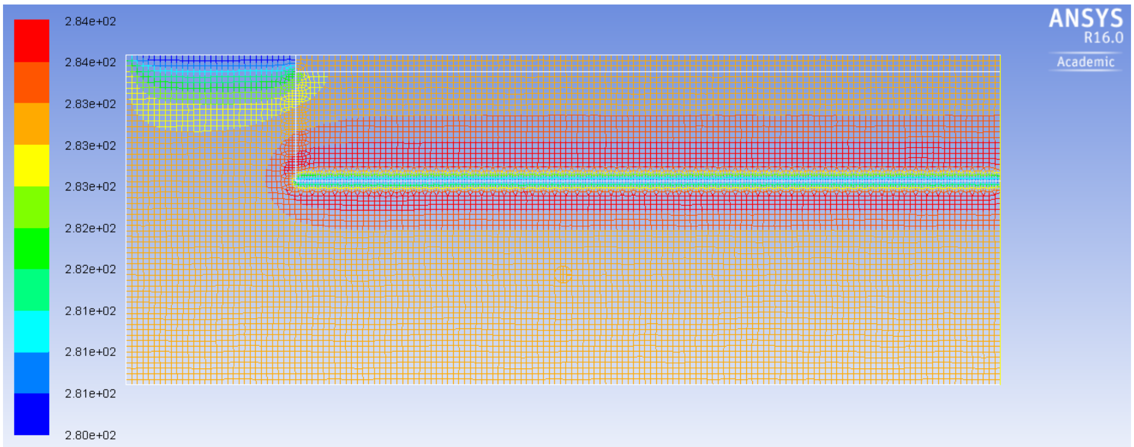

Figure 4.2 - During cold months, heat is transferred from storage to slings. Figure corresponds to simulation in 15^{th} night in January

4.2- Storage size and thermal energy balance

Thermal energy produced by solar collectors is determined by averaging the values obtained from a mathematical model, takings values considered for solar radiation, and energy values obtained from the simulation software Polysun. Thus, the storage charging will be compared with heating consumption.

Figure 4.3 represents the distribution of daily thermal energy consumption versus the energy produced each day by the solar flat-plate collectors. It can be observed how the energy demand increases from November to February due to heating needs. However, from mid-April until lately October, energy produced by solar collectors is higher than heating demand. This is because during summer months, May and period of September-October, only domestic hot water is consumed. Therefore, between these time intervals, excess of thermal heat is stored in the slings of the storage. When heating needs are higher, heat is retrieved from the storage.

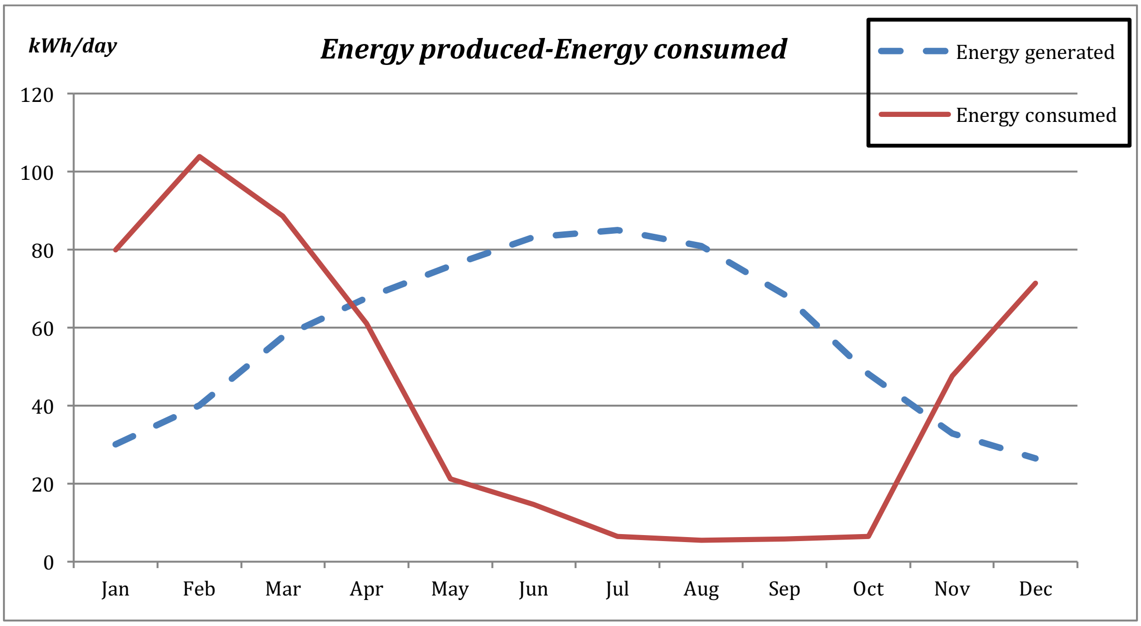

Figure 4.3 - Comparison between daily average distribution of energy produced-consumed

This energy comparison between heat consumed and produced has been constant each day for each month. Nevertheless, uncertainty of weather conditions should be considered since the produced energy curve has been determined if optimal conditions from solar radiation values are obtained. Moreover, the consumed energy might vary in function of the weather since is an irregular phenomenon and cannot be predicted for long-term periods. Also, it should have been considered the hourly consumption for each month to obtain an optimal distribution curve and compare it with real values for heat production in solar collectors.

The monthly charge and discharge of the storage values obtained from simulations and mathematical calculations are presented in figures 4.4 and 4.5. The simulated graph shows the minimum values that must be considered in the storage design. The simulated model describes the maximum storage design parameters. The capacity of the storage comes from values obtained for each month simulations.

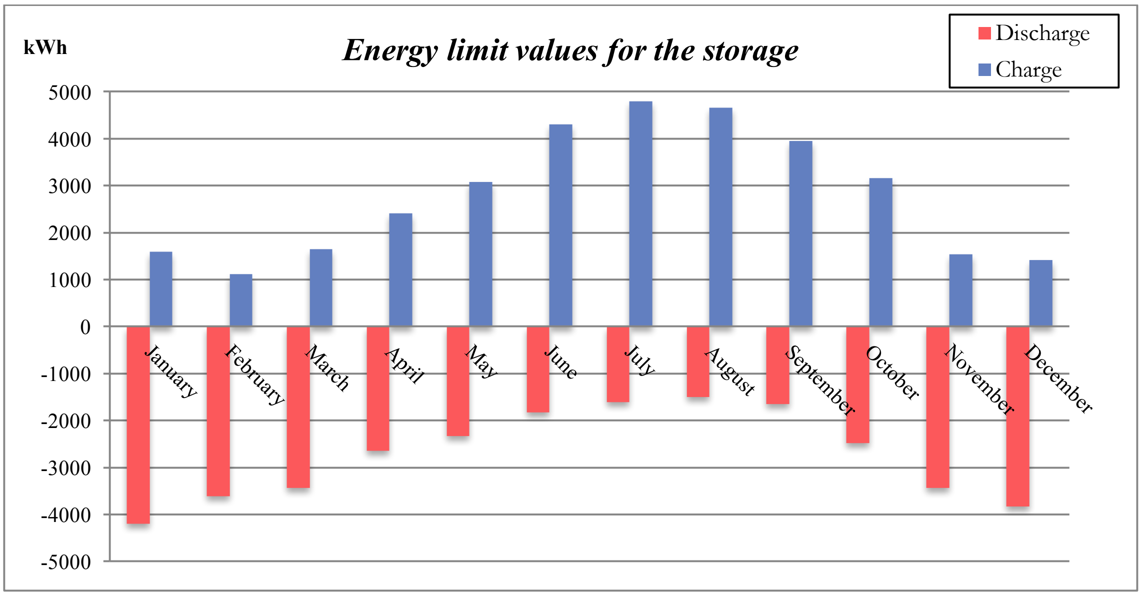

Figure 4.4 - Maximum energy charge/discharge values for each month obtained by the simulated model

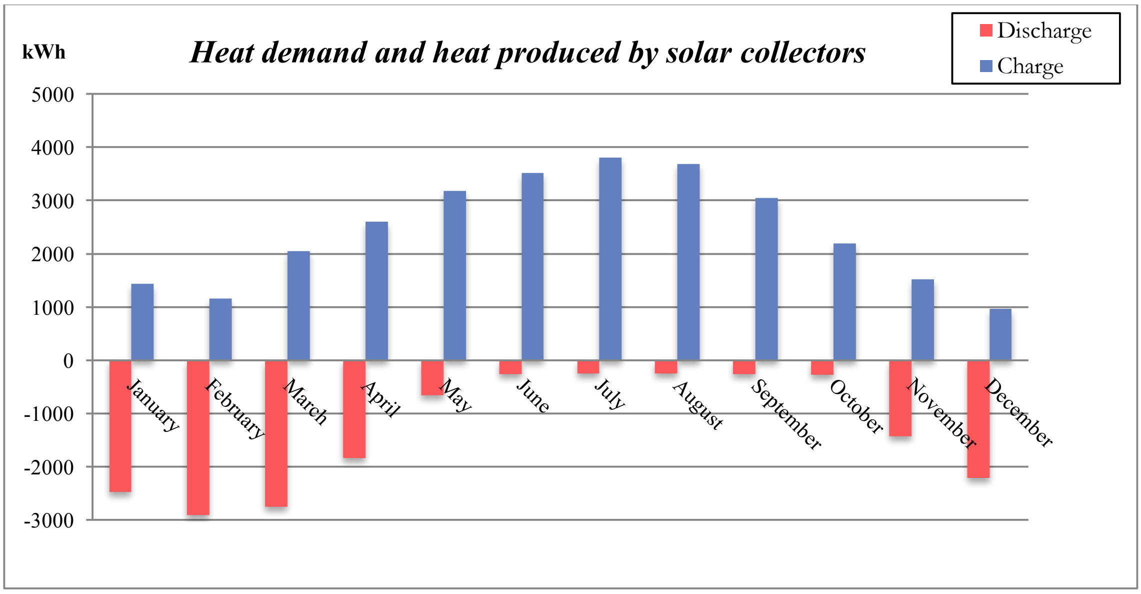

Figure 4.5 - Calculated heat converted from collectors and heat consumption of the house

The calculated discharge presents that in the interval from April to October there is a big potential to expand the storage size. Moreover, during November and March, the calculated energy discharge is lower than the storage design. This indicates that it will be possible to discharge the right amount to cover the heat demand of the building by means of a heat pump. However, the values obtained in the simulated graph are strongly dependent to slings and storage temperatures. A lower temperature running through the slings during day hours will imply a decrease in the energy storage limits.

Besides, it was considered that the flat-plate collectors have standard parameters. In a real situation, by choosing solar collectors with higher efficiency, the solar gain will increase along the year if weather conditions are suitable.

However, there exists an excess of energy produced during summer months. That is, when storage reaches its maximum capacity, which is defined but its dimensions and the simulated model, energy would be lost. There can be different alternatives to make more efficient this system. One possibility is to store the excess heat in an extra accumulator tank to warm the outside pool. Thus, the period to use the pool will increase during colder months and people living in the house will be satisfied knowing that the practice period of the pool has increased. Another option is to disconnect a few solar collectors during summer months, when heating consumption is only due to tap water. In this way, there would be no excess of heat and will imply lower maintenance costs. Instead, there would be the possibility that not enough energy would be generated to store for winter season.

After running all the simulations in Fluent software for designing the storage limits, an analysis of its thermal capacity and energy balance can be done. In figure 4.6, the amount of thermal energy that remains in the storage during each month after the first year is exemplified. The graph suggests that the calculated energy balanced between the charge and discharge of the storage is good since it never gets empty when there is heating demand. However, the storage reaches its maximum capacity, which is determined by its dimensions and thermal conductivity properties to be 5240 kWh, at the beginning of summer months and since there are no heating needs in September and November, during this time, the storage is at its maximum capacity. During this period, the system has an excess heat that should be considered to be more energy efficient.

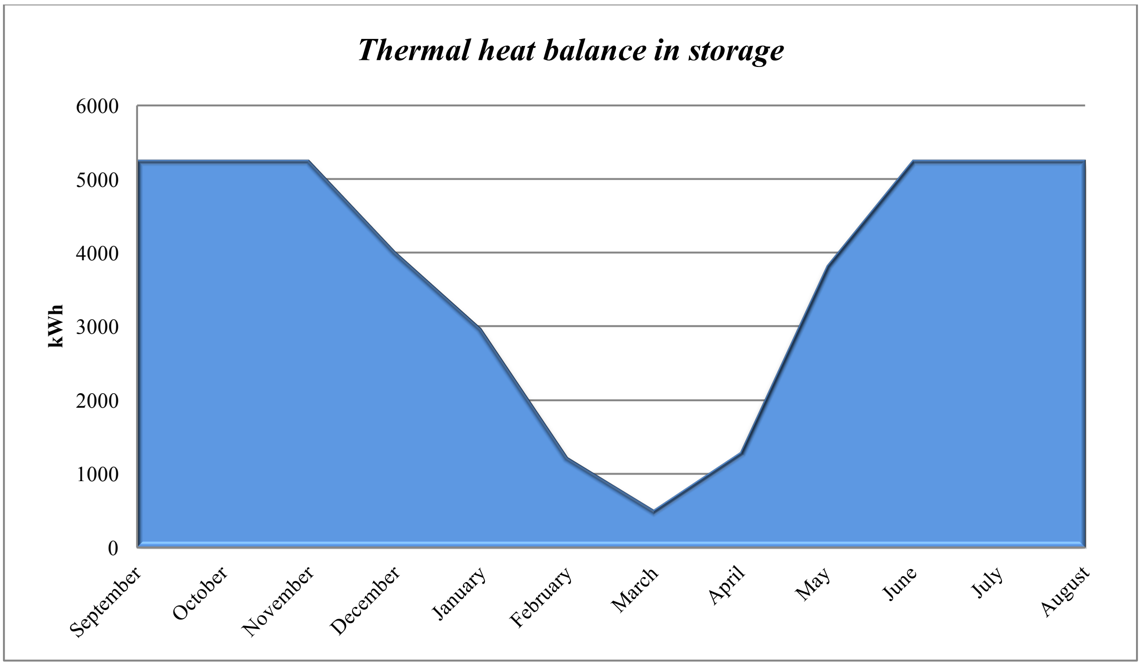

Figure 4.6 - The geothermal storage reaches its maximum capacity from August to October

The storage capacity and size is described by its temperature gradient in the surrounding ground. To increase storage capacity, it may not be needed to expand the area of stone powder. It will be enough to add more solar collectors as long as the mean temperature inside the storage does not exceed 295 K, that would be the maximum temperature in the storage. This temperature was considered because a higher temperature inside the storage will cause thermal conductivity problems with moisture in the stone power that is filling in the storage. [25]

From the mathematical results and the simulated ones, and by knowing the heat demand of the building, as an average, the storage size can be decreased up to 15% and still cover the heat demand of the single-family house. However, it should be considered that the results correspond to the data considered in the project, that is, the consumption and temperatures. Since this technology is dependent on the solar radiation and the house's consumption, there will be uncertainties about the storage dimensions and the capability of supplying all the heating demand.

4.3- Photovoltaic analysis

The main drawback of the photovoltaic resource is the strong dependence to weather conditions and the incident solar radiation. Also, during night hours, there is no energy production.

However, to analyze the possibility to use solar energy in Asturias, figure 4.7 displays the electrical energy generated over the first year by the PV panels installed on the single-family house's roof. During summer months is when more photovoltaic energy can be produced because is when there are more peak sun hours and solar radiation is higher. To increase electricity produced solar panels, the inclination of those should be modified to reach the optimal angle. With this, incident solar radiation will also increase.

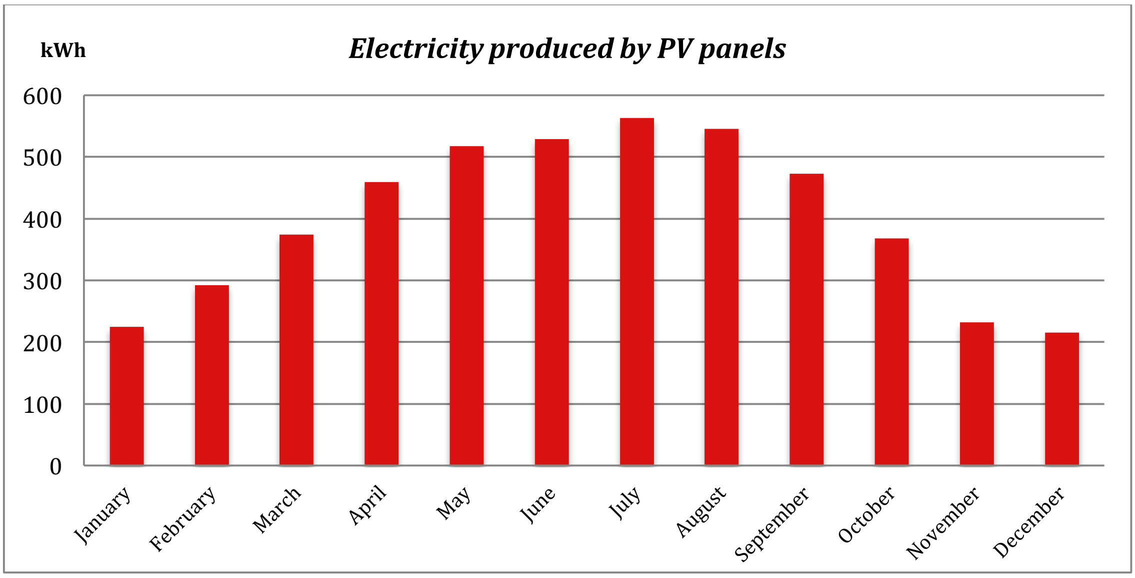

Figure 4.7 - Distribution of electrical energy produced by PV panels during first year of usage

Although the economic viability will be analyzed later, using the net energy metering system, the electrical energy saving due to photovoltaic panels is presented in table 4.1 during the first year.

Annual electricity savings [kWh]	
Consumption	6797,68
PV production	4792
Heat Pump needs	140

Table 4.1 - Electrical energy savings during the first year

Part of the electricity that is produced will be used to feed the heat pump during the months when heat is retrieved from the geothermal storage. Assuming the generation of electrical energy is obtained in optimal conditions, the annual consumption and the heat pump needs (table 4.1), it will imply an annual electrical energy saving of **4352 kWh**.

In figure 4.8, the daily consumption and production for each month is included. It reflects that from late May until beginning of October, there exists an excess of electricity. Since a net energy balance is considered for the house, this energy excess is poured into the grid.

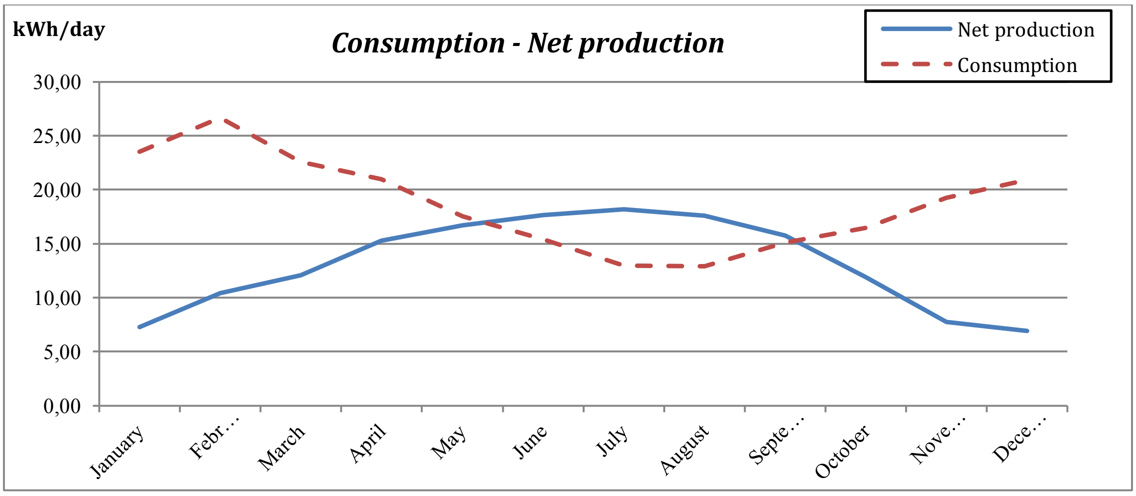

Figure 4.8 - Distribution of electricity consumed in the house and generated by PV panels considering an average day

Due to Spanish Energy policies, the self-production of electricity that is transferred into the distribution grid does not imply any benefit or reduction in costs. This means that during summer months, the installation is overproducing. To obtain a solution, this electricity could be stored in batteries. However, the Spanish government does not have any regulation that implies using NEM system and store energy in batteries. Besides, it will increase the investment due to the batteries. Therefore, to improve the efficiency of the installation, some PV panels may be disconnected during months where solar production is higher than consumption. Nevertheless, it would be better to know the hourly distribution of the consumption and production to have an idea on the time interval where this energy excess occurs. [27]

4.4- Economical and viability analysis

Regarding the study of economic viability, the procedure has been to determine the cost savings that annually would be obtained with both renewable energy technologies.

In order to do so, the first step was to determine the economic outflow of the energy consumption for the single-family house over a year, in the case of not having any of the technologies considered. Values are presented in table 4.2. To carry out the analysis properly, the electricity and gas invoices have been broken down into a series of elements, which are itemized as follows: [28]

◊ Power term: it is a fixed price that results from having available the contracted power at any time. The price is calculated by multiplying the contracted power for the days covered by the invoice and by the power term of the PVPC price that the Ministry of Industry, Energy and Tourism establishes. Currently, the price of the access toll power term is fixed at 42.04352 €/kW·year. The marketing margin is set at 4 €/kW-year. In house object of study, hired power will be established on 4.6 kW.

◊ Energy term: it is a price that is composed of the energy from the access toll (fixed) and of the production cost of the electrical energy in each period (variable). The energy term of the access toll is determined by the Ministry of Industry, Energy and Tourism. Currently fixed at: 0.044027 €/ kWh. The cost of production of electricity is composed of the hourly price of the electricity market, the adjustment services of the system as well as other costs associated with the supply. The cost of electricity production is published on the website of the operator of the Red Eléctrica de España S.A [28]. Average price of the term of cost of the electricity: 0.08 € / kWh. The cost of natural gas production varies in function of the company who sells the energy. As an indicator, prices are chosen for the company Energías de Portugal (EDP) which has a fixed energy access toll of 101.4 €/year for annual consumption greater than 5000 kWh. Average price for the term of cost of natural gas is 0.043876 €/kWh. [22]

◊ Electricity tax: is a special tax whose tax rate has been determined by law since January 1, 2015 (5.1127%). [22]

◊ Natural gas tax: This is a tax on natural gas calculated by multiplying the kWh of consumption owed by 0.00234 € / kWh, equivalent to 0.65 € / GJ, as established in Law 15/2012, of 27 December, on fiscal measures for energy sustainability.

◊ Value added tax (VAT): The current rate on the sum of the previous items is applied (21%).

Annual invoice of the single-family house	
Power term: 4.6 kW [42.04352 €/kW]	193.40 €
Electricity Term: 6797.68 kWh [0.125€/kWh]	849.71 €
Natural Gas Term: 15447.19 kWh [0,043876 €/kWh + 101,4€]	779.16
Electricity Tax [5.1127 %]	43.44 €
Natural Gas Tax [0.00234 €/kWh]	36.15 €
VAT [21 %]	399.39 €
Total annual cost	**2301.25 €**

Table 4.2 - Annual energy invoice of the single-family house without using renewable energies

Facing the analysis of economic viability, it is necessary to highlight that the economical savings will come by the reduction in energy consumption. This will imply that the price of the power term will not be affected and will maintain the same value since no reduction of installed power is desired. Therefore, costs savings will be defined by energy terms, future increases in energy prices and consequent taxes. The feasibility study will only be extended to the first 25 years of life, because a period of higher study would lead to greater uncertainty.

It has been assumed that there is no subsidy for solar photovoltaic or solar thermal installations. Furthermore, it has been considered for the study that the cost of the installation will be with 100% equity.

An approximate increase in consumer price index (CPI) of 3.0% has been taken. This value has been obtained being by averaging the increase in recent years since the European harmonization of this index, as well as an increase in the electricity tariff of 3.0% according to current trends and expectations in Spain. Regarding the price of natural gas, an increase of 3% during the first 10 years and 4% for the 15 years remaining were considered by making an estimation of different hypothesis made by energy consultants, where prices for hydrocarbons and fuels will keep increasing year after year. [6]

The performance of the solar modules is not homogeneous as suffers degradation in its characteristics. By comparing several models, a guaranteed yield of 90% output power for the first 12 years and 80% for the 25 years has been determined for this study. Translating these figures into a guaranteed annual yield drop coefficient results in 0.8%. [7]

The operating expenses include all those necessary for the optimum operation of the system. Thus, operating and maintenance fees and insurance against possible contingencies, will have an annual evolution according to the CPI. According to UNEF estimations, insurance has a cost of 0.3% of the cost of the photovoltaic installation and operating and maintenance costs are estimated at 15 €/kWp per year, a typical value for this type of installation. Maintenance and insurance costs regarding solar collectors and heat pump installations are assumed to be 3.5% of the total cost for the ASES system installation. Due to Law 24/2013, of December 26, of the Electricity Sector, a toll will be applied to the Net Balance system, being estimated in this study with a penalty of 0.030 €/kWh with respect to the energy term. [20], [22]

In order to analyze the feasibility and cost-effectiveness of the renewable energy systems studied, the NPV and IRR method were used as indicators of the results. Microsoft EXCEL sheets have been used to perform the study. In them and according to the assumptions specified so far, the savings and costs of the solar installation have been calculated.

Before calculating savings and maintained costs to determine the feasibility of the project, is important to know how much will cost the initial investment. Since the characteristics of solar panels used in this study are the average of doing a market research, the prices of installation will follow the same steps. Table 4.3 shows how the initial investment has been determined.

Initial investment

Item	Price [€]	Quantity	Total cost [€]
Photovoltaic panels	307	16	4912
Flat-plate collectors	625	10	7250
Investor 24 V/3000 VA/ 50A	538.57	1	538.57
Charge regulator	57.11	2	114.22
Wires and accessories	862.81	--	862.81
Heap Pump (15 kW)	3876.45	1	3876.45
Accumulator tank	789.44	1	789.44
Geothermal Storage	866.74	1	866.74
Installation costs	524.37	--	524.37
Total cost [€]			***18724.6***

Table 4.3 - Breakdown of initial investment for both solar technologies

The price for geothermal storage includes the rental of machinery, worker's salary and the price of the materials that will set the storage up. In installation costs, it has been considered the price for the slings and its connection, as well as other possible extra costs. The same situation was considered in "wires and accessories" for the photovoltaic system.

The operating margin of the systems has been calculated, considering the gains from savings in energy consumption, minus operating expenses, which include maintenance and insurance costs for the facility.

- NPV: the NPV (Net Present Value) is the sum of the updated values of all the expected cash flows of the project, deducting the value of the investment. It measures the viability of the project and is represented by the following formula:

$$NPV(i,N) = \sum_{t=0}^{N} \frac{Rt}{(1+i)^t}$$

where t is the time of the cash flow, i represents the discount rate and R_t refers to the net cash flow.

It is a question of converting future amounts (the Cash Flows of each year) into equivalent current values. For them, the conversion factor i is used, whose value in this project will be i = 5%. The project will be viable if the NPV value is greater than or equal to 0.

- IRR: the IRR (Internal Rate of Return) measures the profitability of the project. It is the rate of discount that makes the NPV of an investment equal to zero. An investment is advisable if the resulting IRR is equal to or greater than that required by the investor. In this case, the rate of return will be 5%.

- Pay-back: the payback period is the time it takes a project to return. The assets allocated to it, being an indicator of risk, since the greater the later the investment recovers, the greater the uncertainty, affecting its profitability. It is interesting to study the pay-back since the shorter the period of recovery of initial investment, the better the project.

Once the indicators to be studied are determined and the initial investment is known, results obtained are analyzed. Appendix B summarizes the analysis of the technologies, considering the annual net energy savings of both installations, understood as such the derivative of the difference between the energy consumed from own solar energy and the energy consumed acquired at the distribution network of the electricity company, having been previously studied in the generation and consumption models.

After calculating the operating margin costs and the cash flow for each year, the economic viability study yields in a payback period for 10 years. Table 4.4 figures the values obtained for NPV and IRR. The analysis reflects that this project would be feasible in a period of 25 years, where after year 10^{th}, total cost of the investment made would be recovered. Since the IRR is greater than the assumed rate of return (5%), the installation of the systems is viable.

Economic results	
Payback [years]	10
VNP	23.916,37 €
IRR	9,64%

Table 4.4 - Main indicators for the economic study of the two solar technologies

5. Discussion

As it was described at the beginning of the project, the high national energy dependence, social and environmental awareness of citizens facing climate change and the depletion of non-renewable resources mean that, for the future, investing on renewable energies would be the solution. Although in near future, the electricity production regime is still marked by thermal power plants, the continued growth in coal consumption in countries such as China or India, despite the current economic crisis, may endanger the economy of thermal energy sector in Spain, rising considerably the price of fuels, which would lead to an increase in the price of electricity. [20]

A solution might be the use of renewable energies to reduce the consumption of conventional energies. However, besides the different renewable resources, these are not available in all parts, that is, renewable energies depend on the location. Thus, this project was focused in two solar technologies, which have big dependence to weather conditions. This will imply uncertainties and sources of errors. Having an extreme cold winter or a long cold season will imply higher energy consumption and the storage might not be designed for these situations. Then, energy storages as electrical batteries o thermal storages could be designed to account for this type of uncertainties. Thus, the two solar technologies were designed considering the data from last years and analysis result in that are technologically viable. So, the future of these technologies will depend on things that will occur in future years.

The solution of self-consumption in the net balance regime helps to take advantage of all the local generation, either through instantaneous or deferred consumption with the help of consumption rights generated when surpluses occur. Self-consumption will be cost-effective when grid parity is reached, that is, where both the price of electricity in the market and the local generation cost itself influence. In addition to the economic barriers, Spain must solve the many legal barriers that currently exist, and which do not seem to be solved in recent years with the new policies that are being applied in the Electricity Sector.

6. Conclusion

A relationship between storage behavior and building heat demand has been found. The heat demand of the building will come from solar collectors, storage and heat pump electricity. The monthly heat needed from storage is found when separating the different heat inputs. This is compared to the heat that is left in the storage each month.

Results show that ASES system is in its basic design dimensioned larger than needed for the full year and it should be optimized. The storage may be made smaller and still be designed to cover the annual heating demand.

The simulations refer to the first year of a system usage. The ground temperature will be stable after a couple of years and the storage behavior will mainly change due to weather. The ground warming over the years will imply a decrease in thermal losses. Still, the ASES system and geothermal storage will need to be dimensioned so that it fully functions the first year after installation. The storage design is simulated using weighted average each month of a year only specifying day and night. This is a simplification of the model. The model would be more accurate if simulations were done hourly, specifying how ambient temperature changes, as well as slings temperatures.

The temperatures in the air and the slings had been determined by an average and are fixed for each month. Moreover, the temperature distribution on the ground is non-linear. Thus, mathematical errors have been made when determining the initial ground temperatures. Due to climate change, there is an increase in annual mean temperatures bringing with it long periods of drought and strong rainstorms, wind and cold. This causes that values obtained in this project might be altered at any year.

Photovoltaic panels where installed on the single-family house's roof to cover partially the electricity demand, reaching 65% of annual consumption with optimal conditions. However, considering the same problem that the solar collectors present on the strong dependence to the weather conditions, the time difference between the energy production of the PV panels and the hours of consumption has not been considered. This means that electricity generated during the day is consumed during hours with zero production and consumption is high, i.e. at night. This is an important inaccuracy that should be consider in further work, since it has been considered a net energy metering system and not with storage in electrical batteries.

To end the project, an economic analysis was done to study the feasibility of using these two solar technology installations. To do so, several factors have been considered and predictions on how much energy prices would vary. Therefore, it cannot be exact values, since in the future, any political, ideological or nature reason would imply a drastic change in the values used. However, the objective of this project was to analyze the possibility of implementing systems that use solar energy to meet the energy demands of a single-family house. It has been seen that with the ASES system, it is possible to cover the total consumption of heating and domestic hot water with help of a heat pump. On the other hand, the implementation of photovoltaic panels that take advantage of solar energy, allows achieving annual savings of 65% in electrical power in optimal conditions during the first year.

Considering the ideal situation assumed in this project, figure 6.1 reflects the evolution of the NPV over the years. Economic analysis reflects that payback period results to occur in year 10. Considering that the internal rate of return for the whole system has been obtained greater that the rate of return, it suggests that, the use of solar energy in the city of Gijón, and in general, in the region of Asturias, may have a promising future if the laws and political measures of Spain, permit and favor the development of renewable energies.

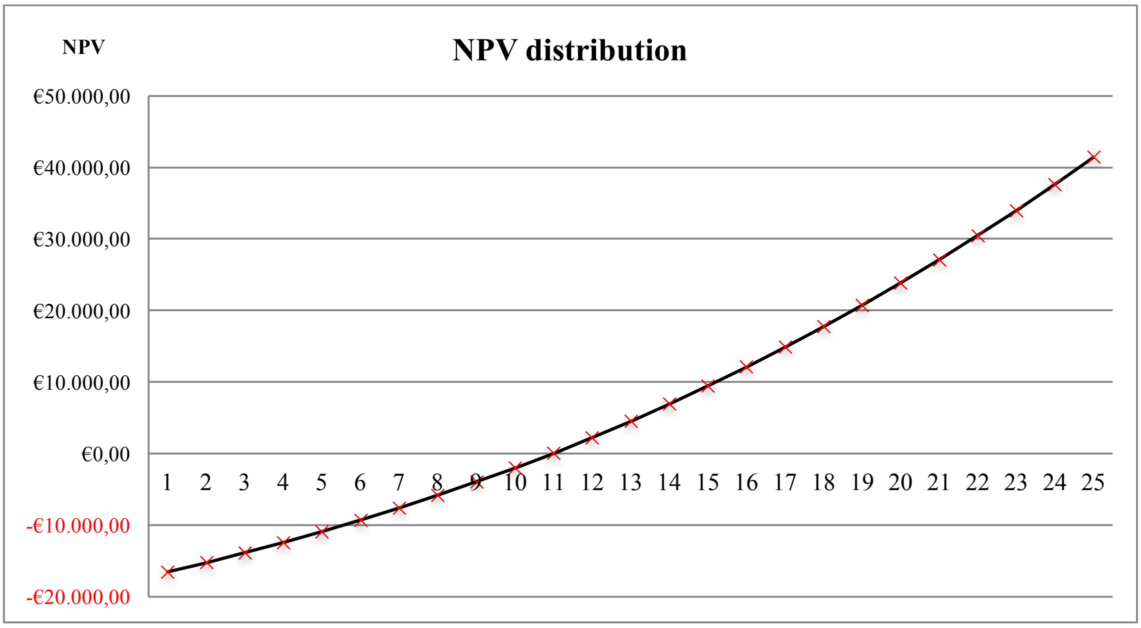

Figure 6.1 - Distribution of NPV during 25 years of the economic study for both solar technologies

Besides the economic savings that the implementation of these renewable technologies would imply, it also contributes to reduce GHG emissions, especially CO_2 that would be produced from conventional energy sources when generating energy. To obtain an initial estimation of these reductions, with just the ASES system applied to this house and working with the data considered, it will reduce up to 7,014 kg of CO_2, which is an important amount.

To resume, after the realization of this project, three main ideas can be concluded:

1) Non-renewable energy consumption may be reduced in the residential sector by using these solar technologies.
2) These technologies are energetically and economical viable.
3) There is a need for new energy regulations favoring the development of renewable energies.

6.1- Further work

After the conclusion of this research project it turns out that it is viable the use of renewable technologies that take advantage of the solar energy to feed a single-family house. However, as this was an initial project, there would still be a lot of work to do to know about the real technical-economic feasibility of these technologies. Since these are systems dependent mainly on solar exposure, the calculations should be optimized to determine the hours at which the energy is produced and when it is consumed. It would be necessary to know the different moments of production-consumption that in this project were considered constant for each day and month of the year.

In addition, a solution should be sought in order to optimize and improve the efficiency of the technologies. This happens to make analysis during the months when production of solar energy, thermal and photovoltaic, is higher to the demand. During this period, the systems do not take advantage of this energy excess.

On the other hand, and perhaps the most important condition for these renewable energy projects for self-consumption in housing are the regulations and laws established by the Spanish government. The current energy law has been known and criticized by the famous "sun tax". With this law, Spanish electrical system is plagued with measures against the development of renewable energy. That is why the situation of renewable energies in Spain is no longer quite dependent on its technology. The evolution of renewable energy development will be marked by the laws and regulations dictated in future by the Spanish government.

6.2- The future is bright

A solution to overcome the intermittent availability of solar power is the addition of an energy storage to a PV installation. It would help bringing solar energy into line with more traditional energy sources in terms of dispatchability, stability and control. Moreover, as Levran, A. says in its article “Solar Power”, the persistent development of storage technology is essential to speed the crossing toward a future marked by self-consumption, self-sufficiency and the flawless integration of solar sources into electrical power grids worldwide. [21], [34]

Subsidies for photovoltaic in the main European markets have become unviable and are being scaled down. However, these are not bad news for solar energy generation. Development and improvement of new technologies that meant significant reduction costs together with an increase in retail tariffs have converted PV technology from a severely subsidized and marginal resource into a majority and competitive energy source. Year after year, more residential households are installing solar systems on their roofs for electricity and heating generation so to reduce their energy bills. Such installations can be achieved without subsidies and can attain an IRR more than 6 percent and a payback period of under 10 years, as almost can be obtained in the project developed. [34]

7. References

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Appendix A: CFD simulation pictures

In this appendix, simulation pictures of the geothermal storage are presented. The results correspond to transient simulations after 15 days and nights for each month. The scale of temperatures has been modified for each picture in function of the minimum and maximum temperatures in the storage.

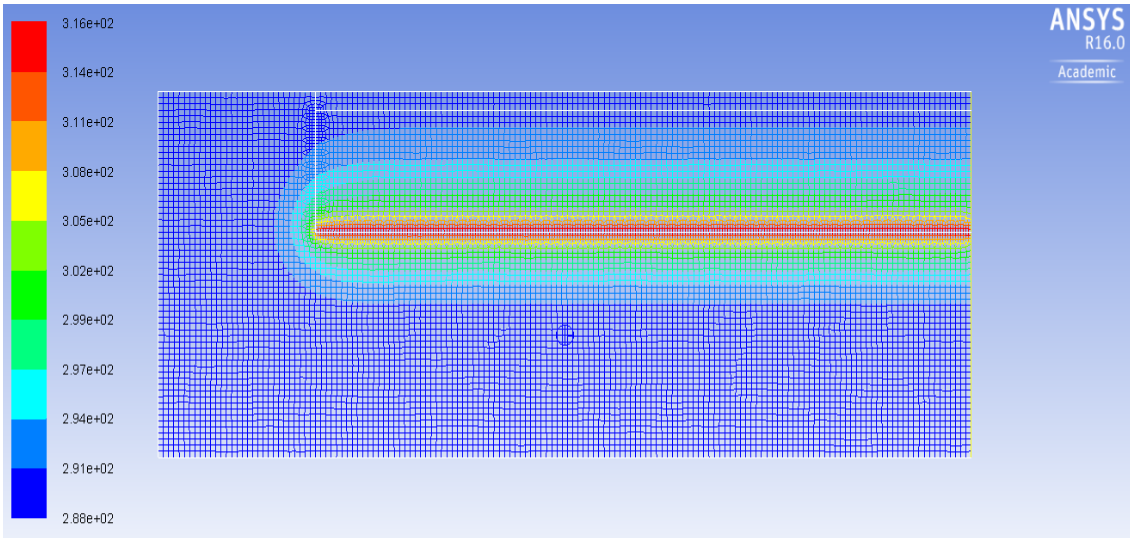

Figure A 1. June 15th day simulated temperature gradient in the storage

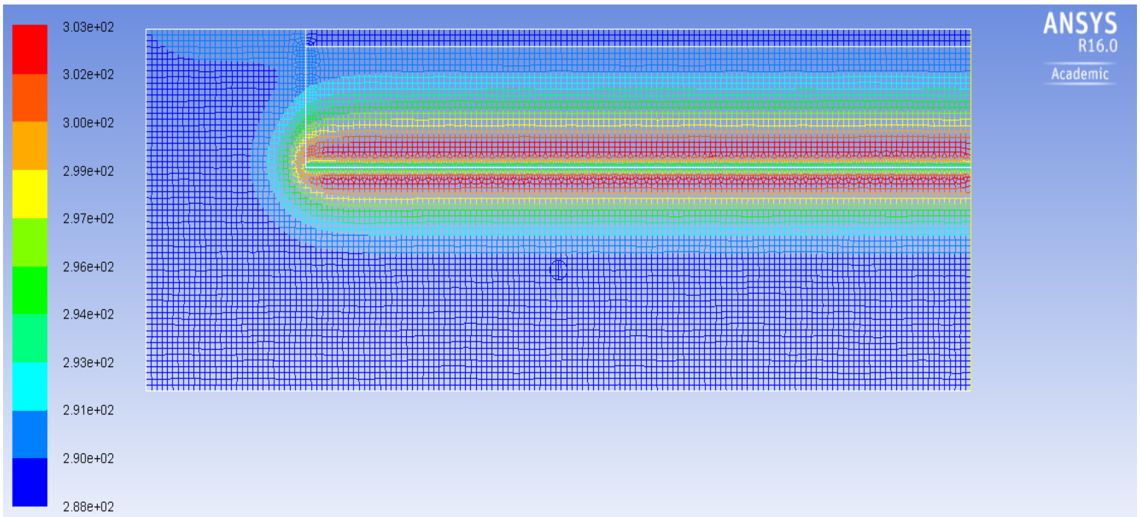

Figure A 2. June 15th night simulated temperature gradient in the storage

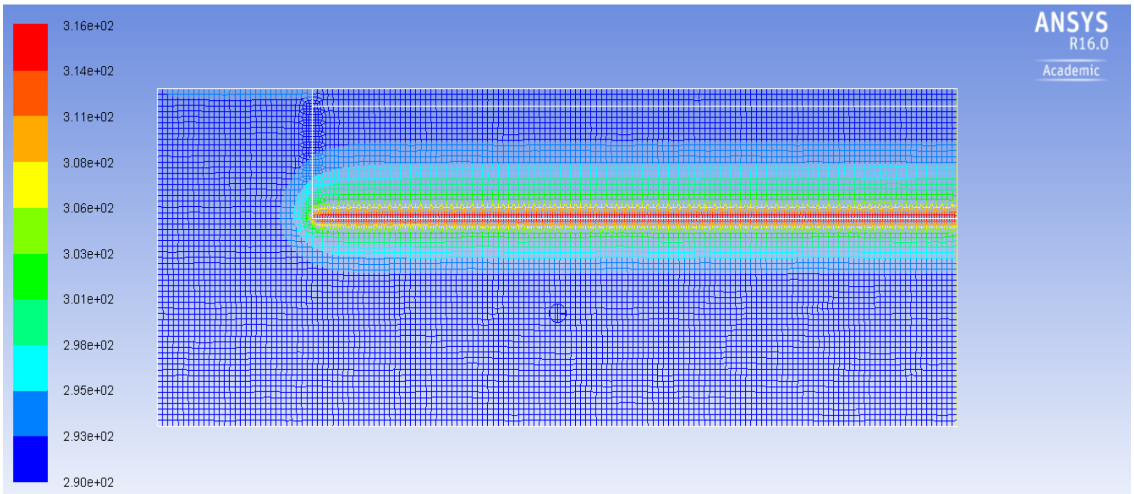

Figure A 3. July 15th day simulated temperature gradient in the storage

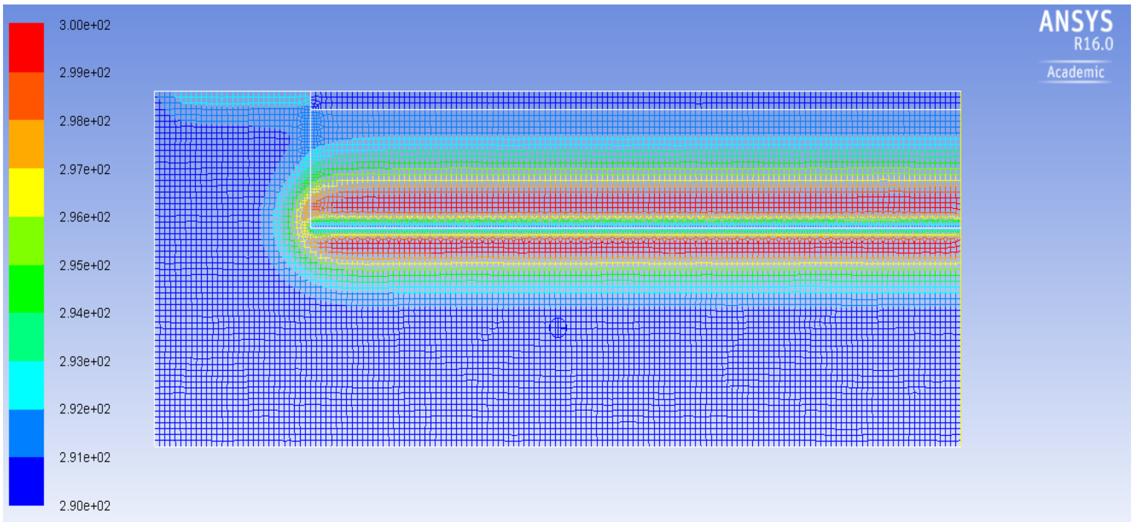

Figure A 4. July 15th night simulated temperature gradient in the storage

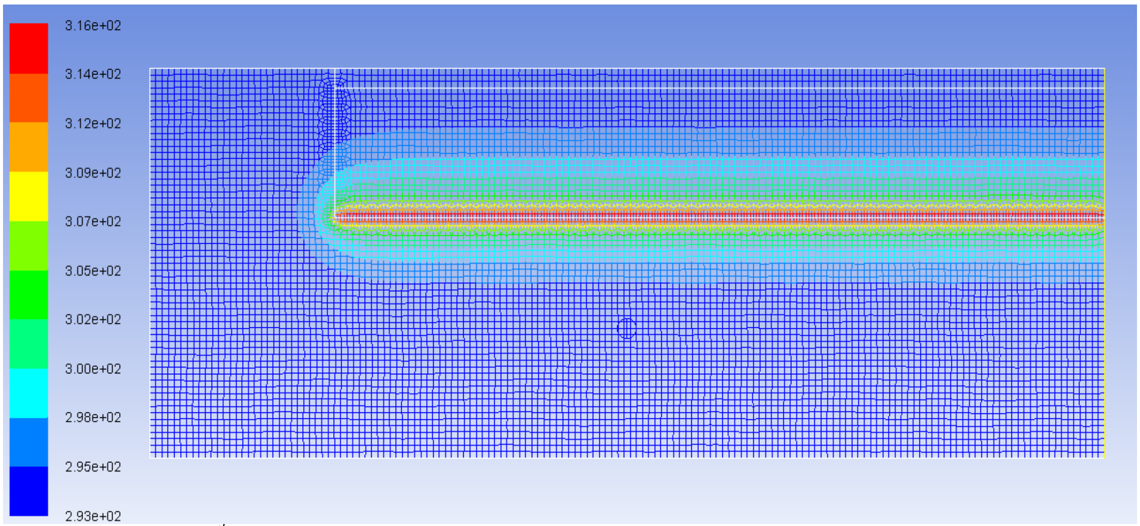

Figure A 5. August 15th day simulated temperature gradient in the storage

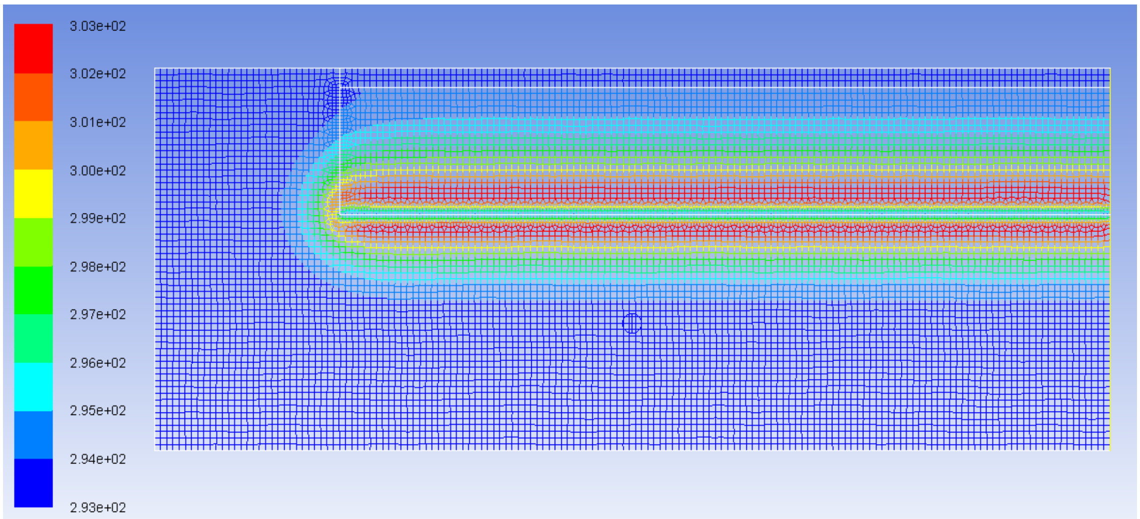

Figure A 6. August 15th night simulated temperature gradient in the storage

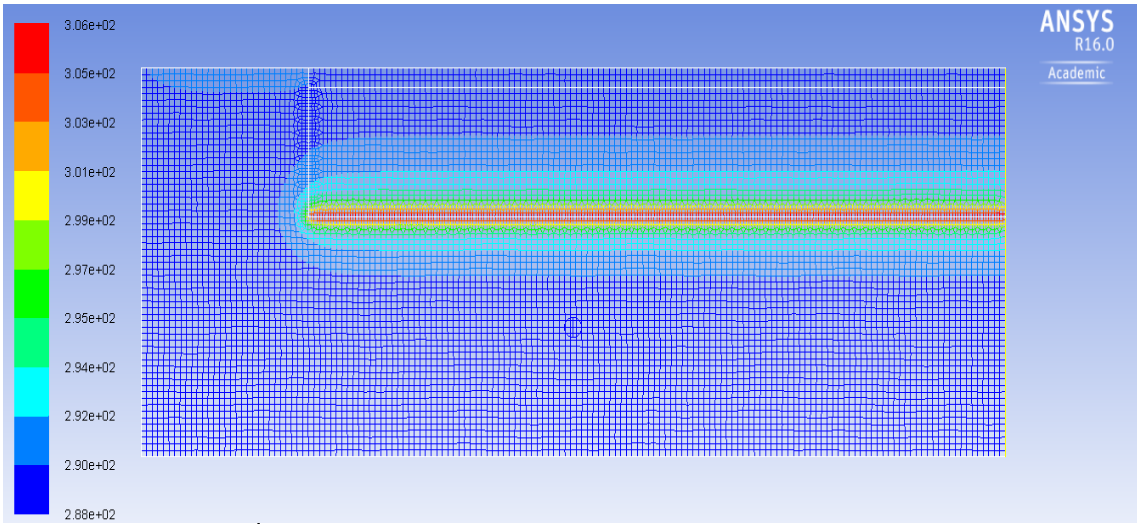

Figure A 7. September 15th day simulated temperature gradient in the storage

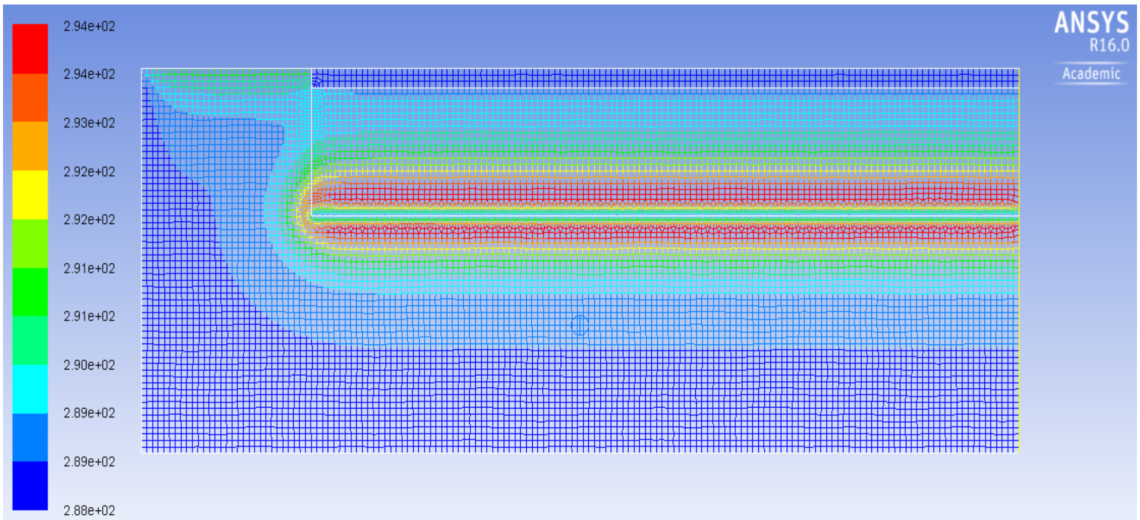

Figure A 8. September 15th night simulated temperature gradient in the storage

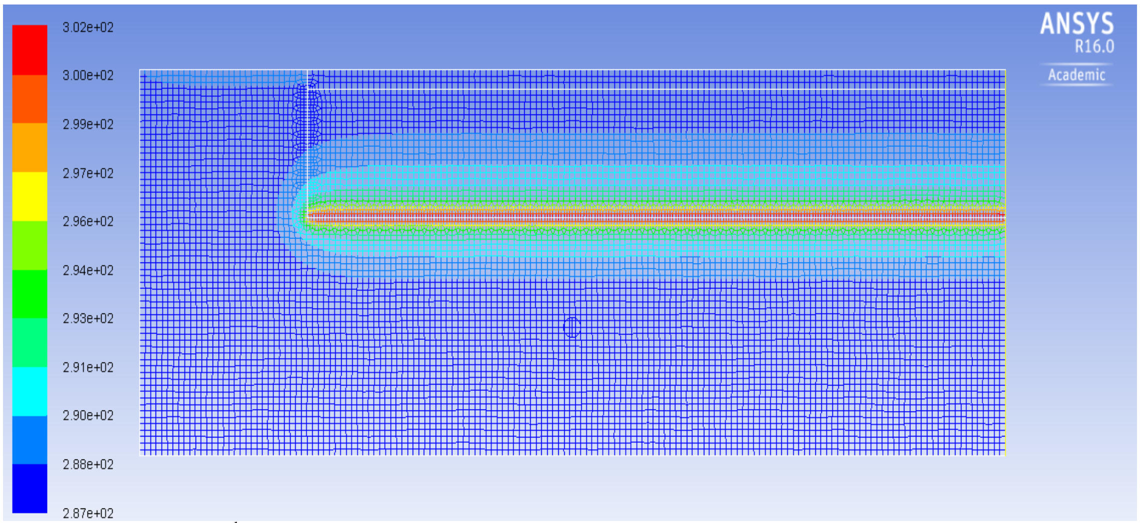

Figure A 9. October 15th day simulated temperature gradient in the storage

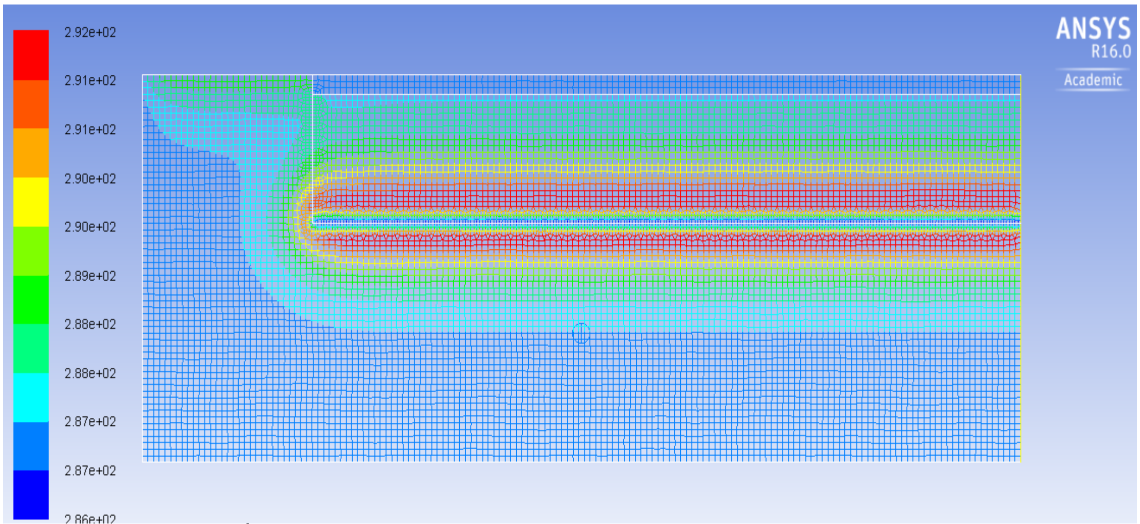

Figure A 10. October 15th night simulated temperature gradient in the storage

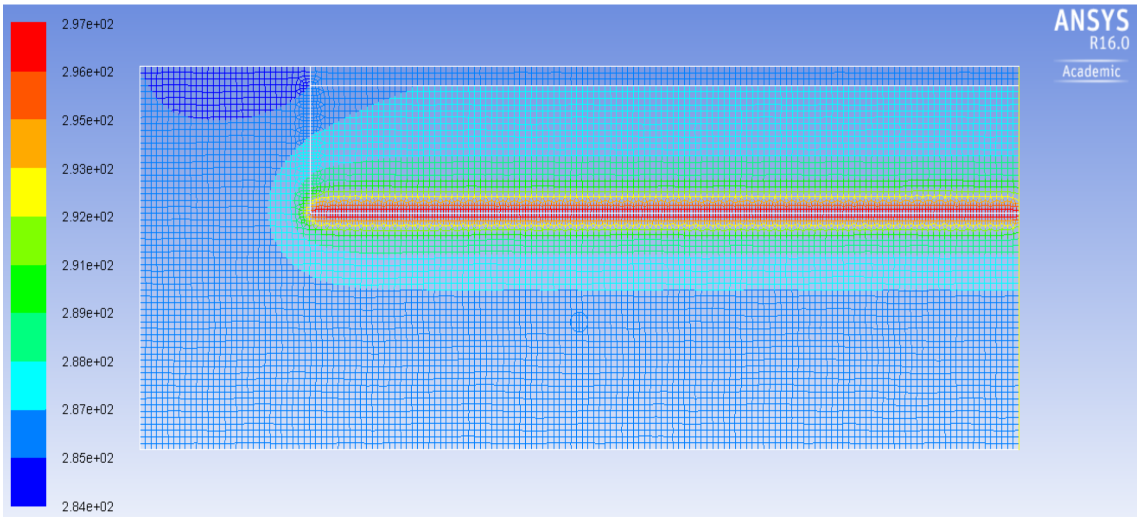

Figure A 11. November 15th day simulated temperature gradient in the storage

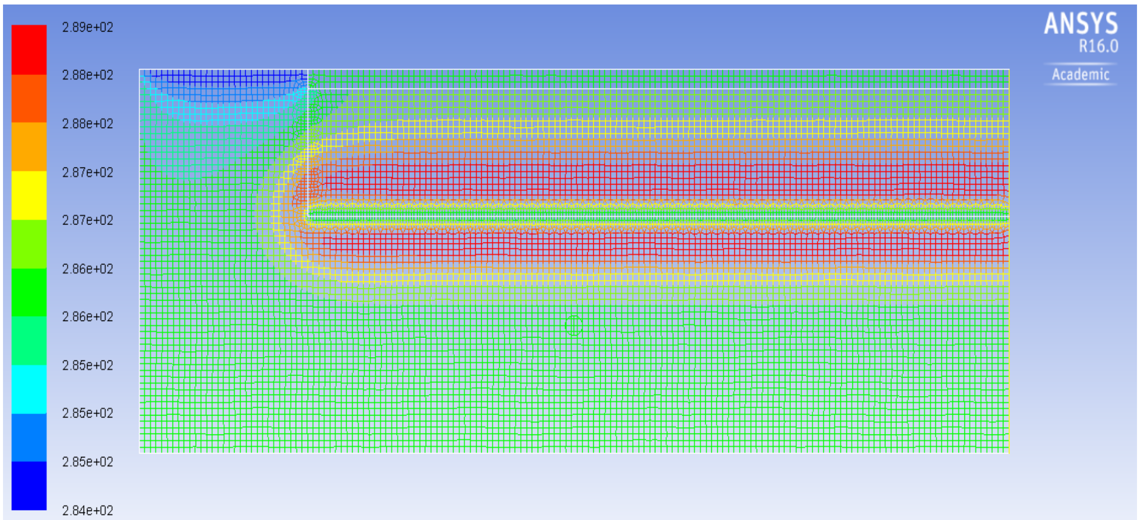

Figure A 12. November 15th night simulated temperature gradient in the storage

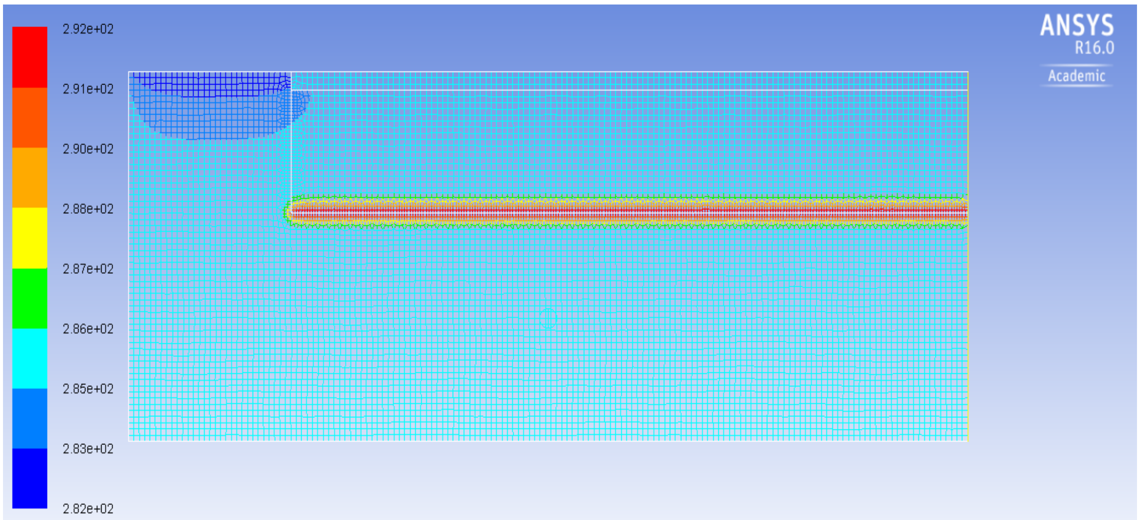

Figure A 13. December 15th day simulated temperature gradient in the storage

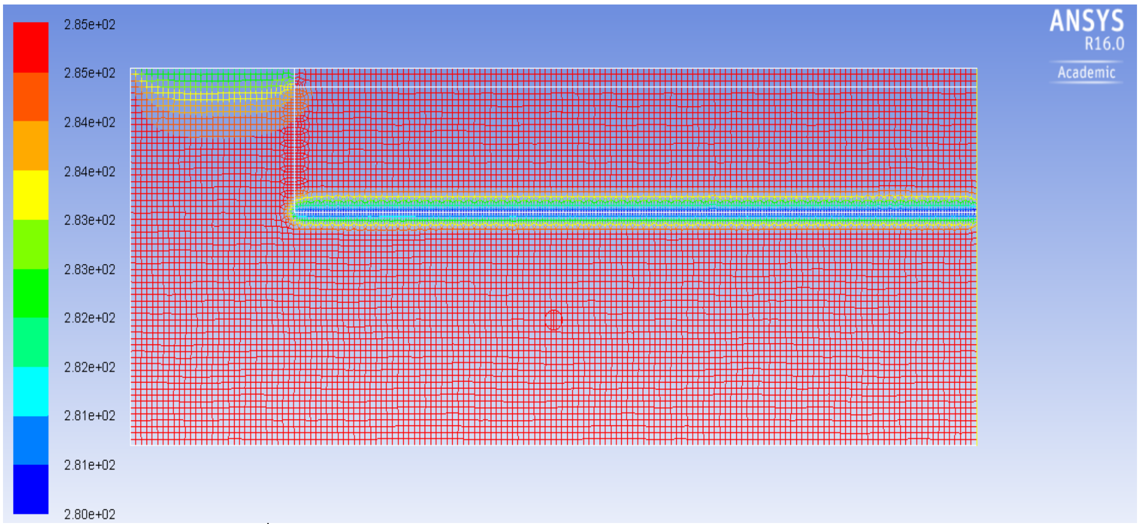

Figure A 14. December 15th night simulated temperature gradient in the storage

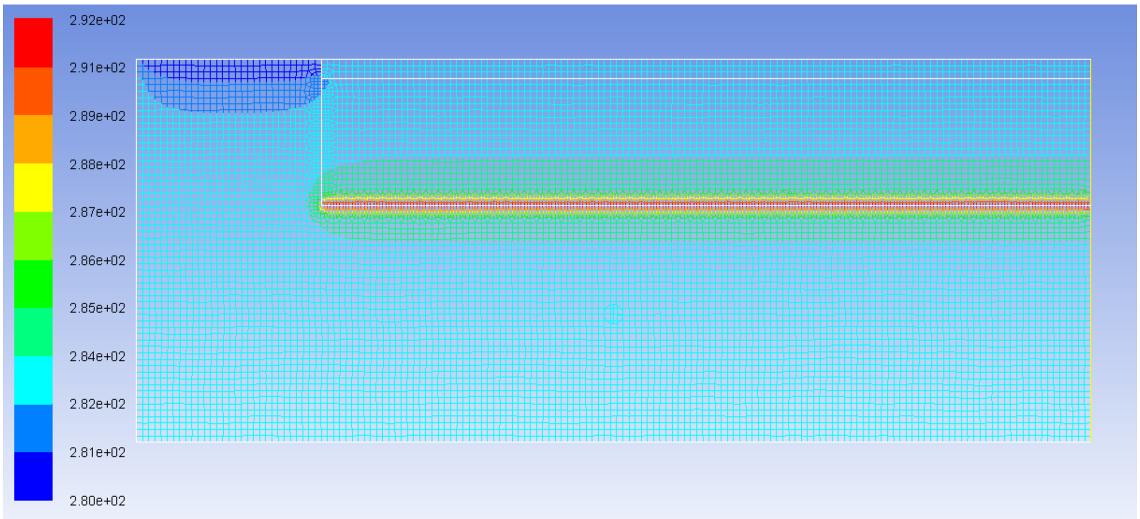

Figure A 15. January 15th day simulated temperature gradient in the storage

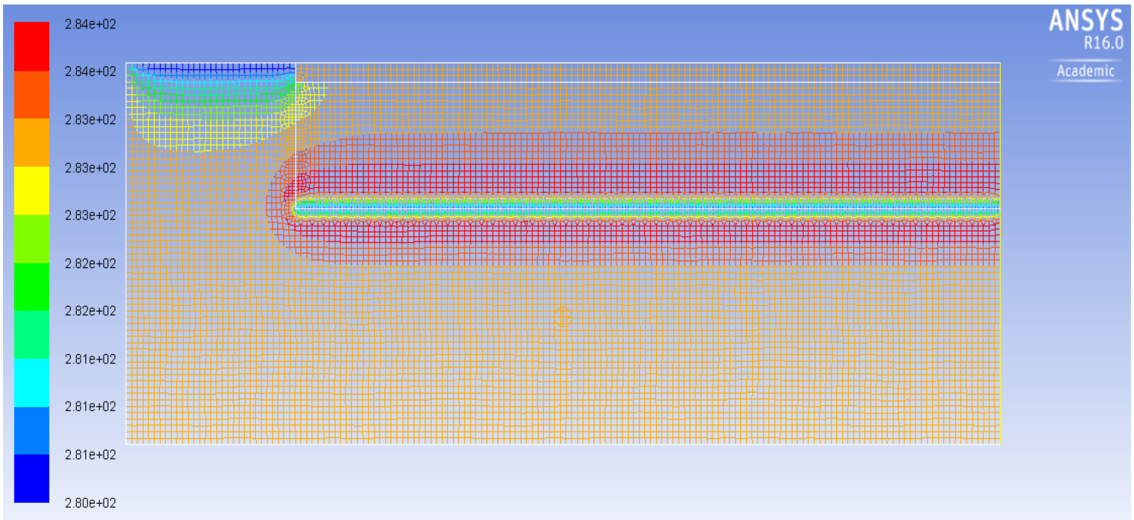

Figure A 16. January 15th night simulated temperature gradient in the storage

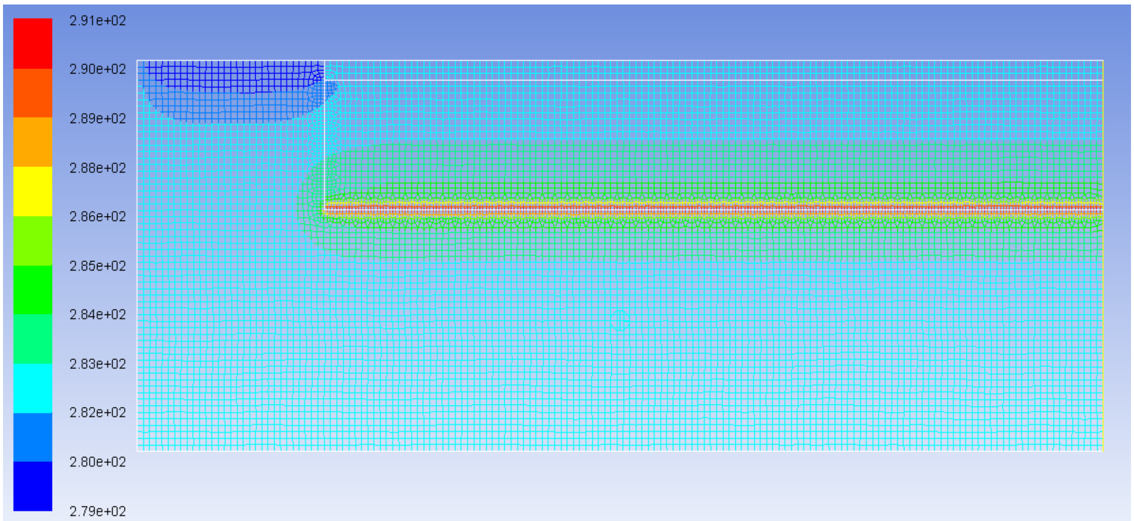

Figure A 17. February 15th day simulated temperature gradient in the storage

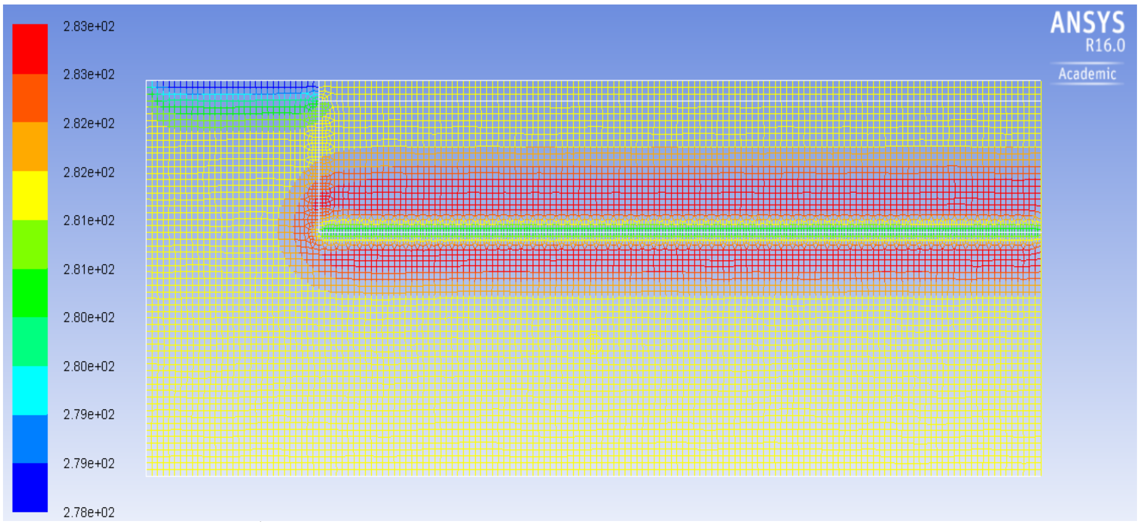

Figure A 18. February 15th night simulated temperature gradient in the storage

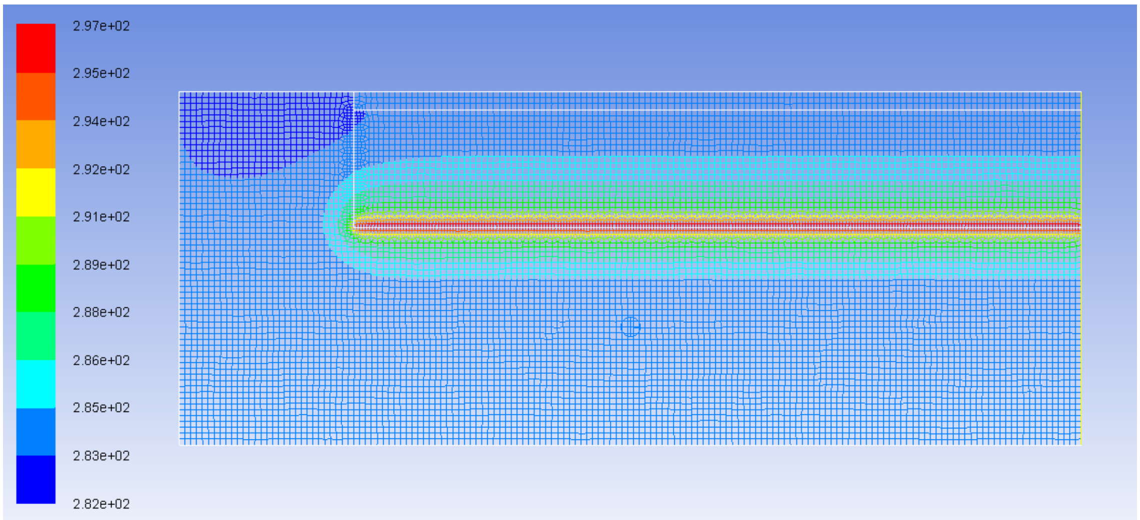

Figure A 19. March 15th day simulated temperature gradient in the storage

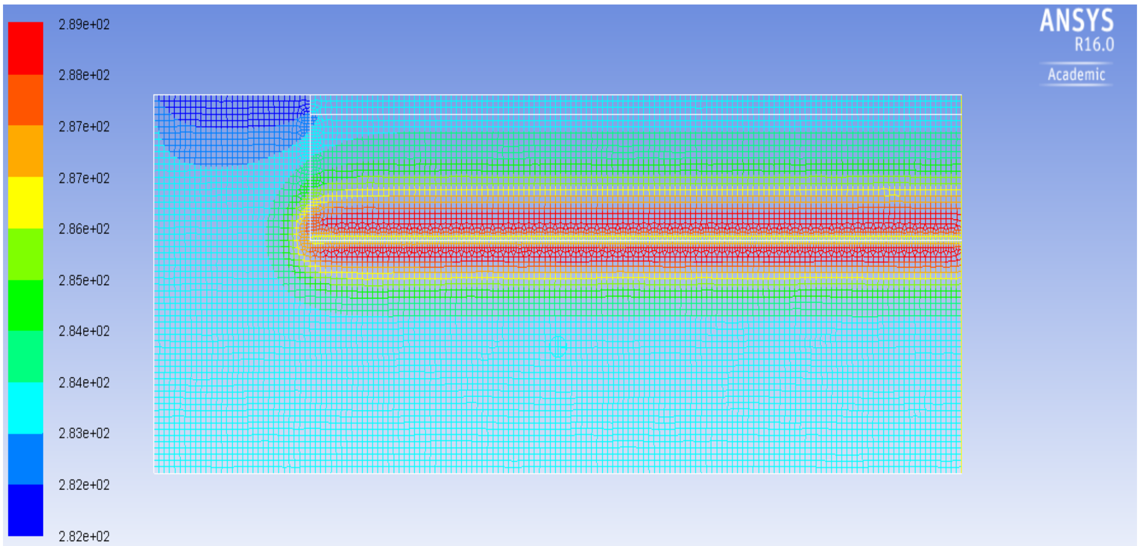

Figure A 20. March 15th night simulated temperature gradient in the storage

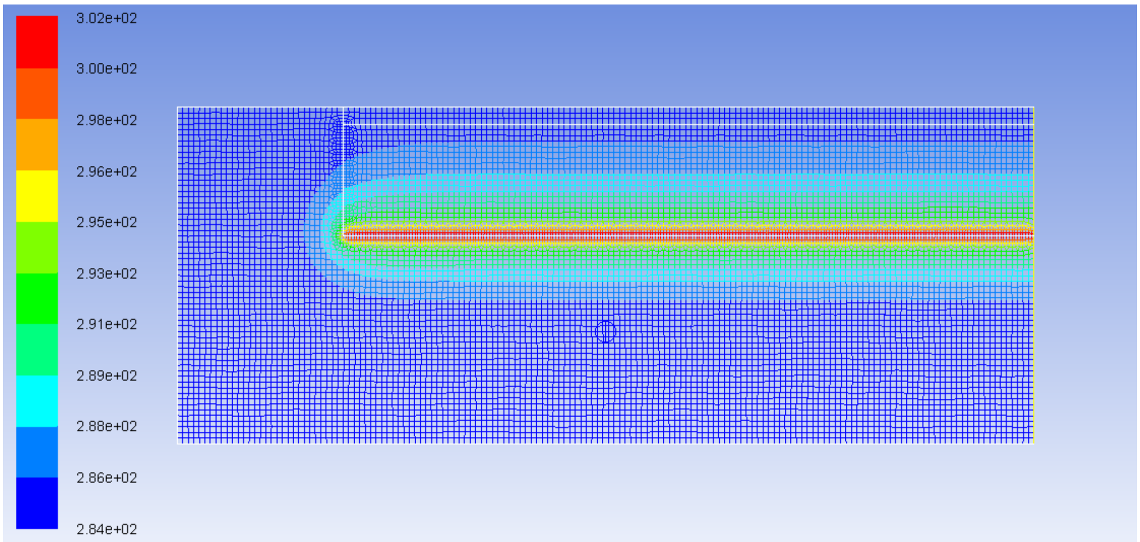

Figure A 21. April 15th simulated temperature gradient in the storage

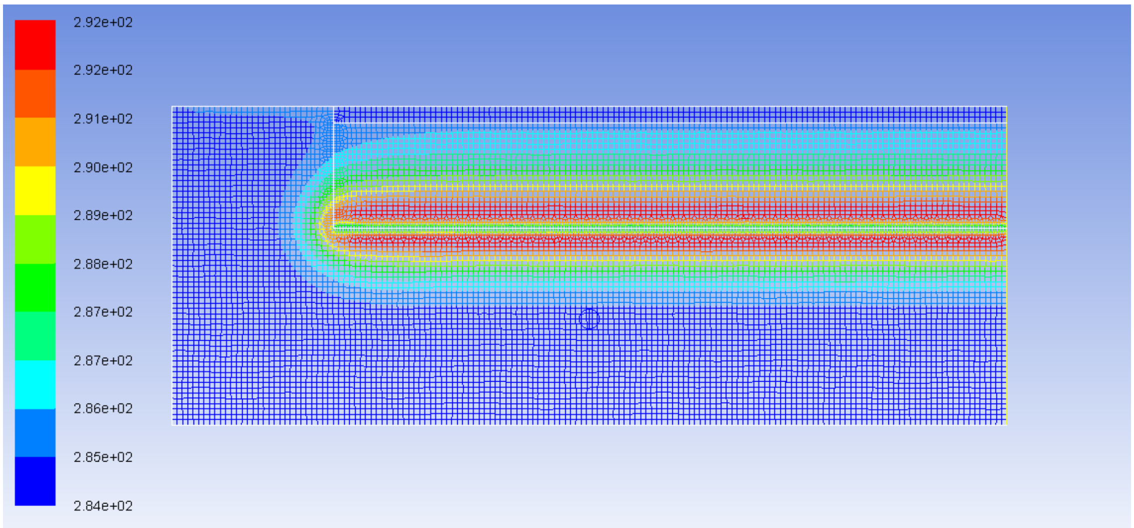

Figure A 22. April 15th simulated temperature gradient in the storage

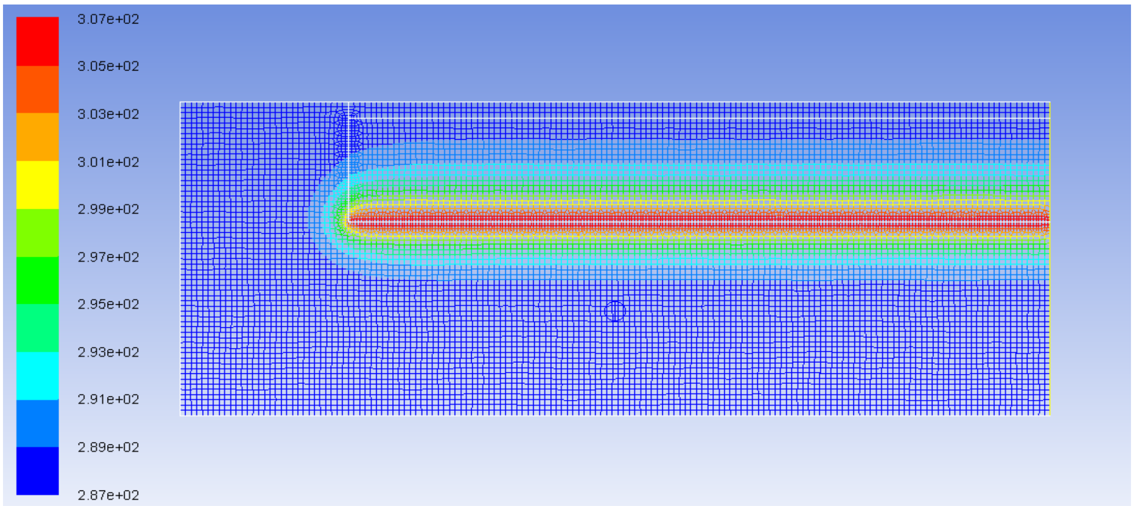

Figure A 23. May 15th day simulated temperature gradient in the storage

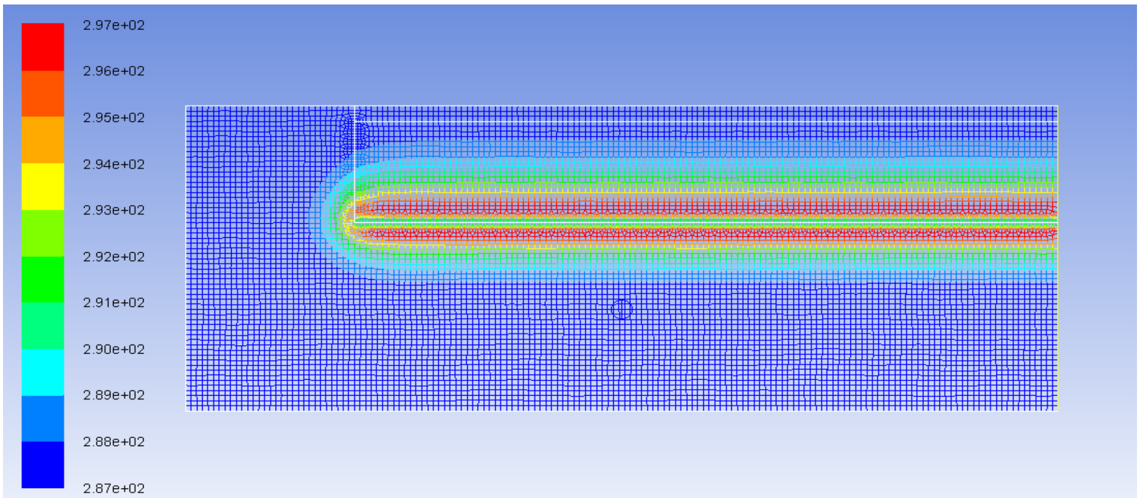

Figure A 24. May 15th night simulated temperature gradient in the storage

Appendix B: economic analysis

The following table represents the evolution of the economic study during 25 years of lifetime representing the distribution of the NPV.

Year	Thermal energy production [kWh]	Electricity production [kWh]	Natural gas price [€/kWh]	Electricity price [€/kWh]	Income [€]	Costs [€]	Cash-flow [€]	Cash-flow accumulated [€]	NPV
	0	0	--	--	-18734,60	0	-18734,60		
2017	21220,02	4855,00	0,05	0,18	1837,66	507,63	1330,03	-17404,57	-16.575,78 €
2018	21050,25	4816,16	0,05	0,18	1883,55	522,86	1360,70	-16043,88	-15.279,88 €
2019	20881,85	4777,63	0,05	0,19	1980,73	538,54	1442,19	-14601,69	-13.906,37 €
2020	20714,80	4739,41	0,06	0,20	2079,57	554,70	1524,87	-13076,82	-12.454,11 €
2021	20549,08	4701,49	0,06	0,21	2180,12	571,34	1608,78	-11468,04	-10.921,94 €
2022	20384,69	4663,88	0,06	0,21	2282,41	588,48	1693,93	-9774,10	-9.308,67 €
2023	20221,61	4626,57	0,07	0,22	2386,49	606,13	1780,36	-7993,74	-7.613,09 €
2024	20059,84	4589,56	0,07	0,23	2492,40	624,32	1868,08	-6125,66	-5.833,96 €
2025	19899,36	4552,84	0,08	0,24	2600,19	643,05	1957,14	-4168,52	-3.970,02 €
2026	19740,16	4516,42	0,08	0,25	2709,88	662,34	2047,55	-2120,98	-2.019,98 €
2027	**19582,24**	**4480,29**	**0,09**	**0,25**	**2845,34**	**682,21**	**2163,14**	**42,16**	**40,15 €**
2028	19425,58	4444,45	0,09	0,26	2984,88	702,68	2282,21	2324,37	2.213,68 €
2029	19270,18	4408,89	0,10	0,27	3128,65	723,76	2404,89	4729,26	4.504,06 €
2030	19116,02	4373,62	0,11	0,28	3276,78	745,47	2531,31	7260,57	6.914,83 €
2031	18963,09	4338,63	0,11	0,29	3429,45	767,83	2661,61	9922,19	9.449,70 €
2032	18811,38	4303,92	0,12	0,30	3566,74	790,87	2775,87	12698,05	12.093,38 €
2033	18660,89	4269,49	0,13	0,30	3708,60	814,59	2894,01	15592,06	14.849,58 €
2034	18511,61	4235,33	0,14	0,31	3855,20	839,03	3016,17	18608,23	17.722,13 €
2035	18363,51	4201,45	0,15	0,32	4006,71	864,20	3142,51	21750,74	20.714,99 €
2036	18216,61	4167,84	0,15	0,32	4163,30	890,13	3273,17	25023,91	23.832,30 €
2037	18070,87	4134,50	0,16	0,33	4325,16	916,83	3408,32	28432,24	27.078,32 €
2038	17926,31	4101,42	0,17	0,34	4492,46	944,34	3548,13	31980,36	30.457,49 €
2039	17782,90	4068,61	0,18	0,34	4665,41	972,67	3692,75	35673,11	33.974,39 €
2040	17640,63	4036,06	0,19	0,35	4844,21	1001,85	3842,37	39515,48	37.633,79 €
2041	17499,51	4003,77	0,21	0,36	5029,07	1031,90	3997,17	43512,65	41.440,62 €

Table B 1. Break-down of the economic study, reflecting the NPV

Appendix C: Heating energy comparison

In figure C1, a comparison between the household's heating, domestic hot water and solar gain is showed. As it can be seen, the total solar gain by the 10 solar collectors is lower than the total solar radiation incident on them, as it was expected. However, values show a closer proximity in the autumn season that could be motivated by weather factors that have been considered. Another assessment that can be taken is observing how, from July to October, the house's heating demand is due to heating domestic water.

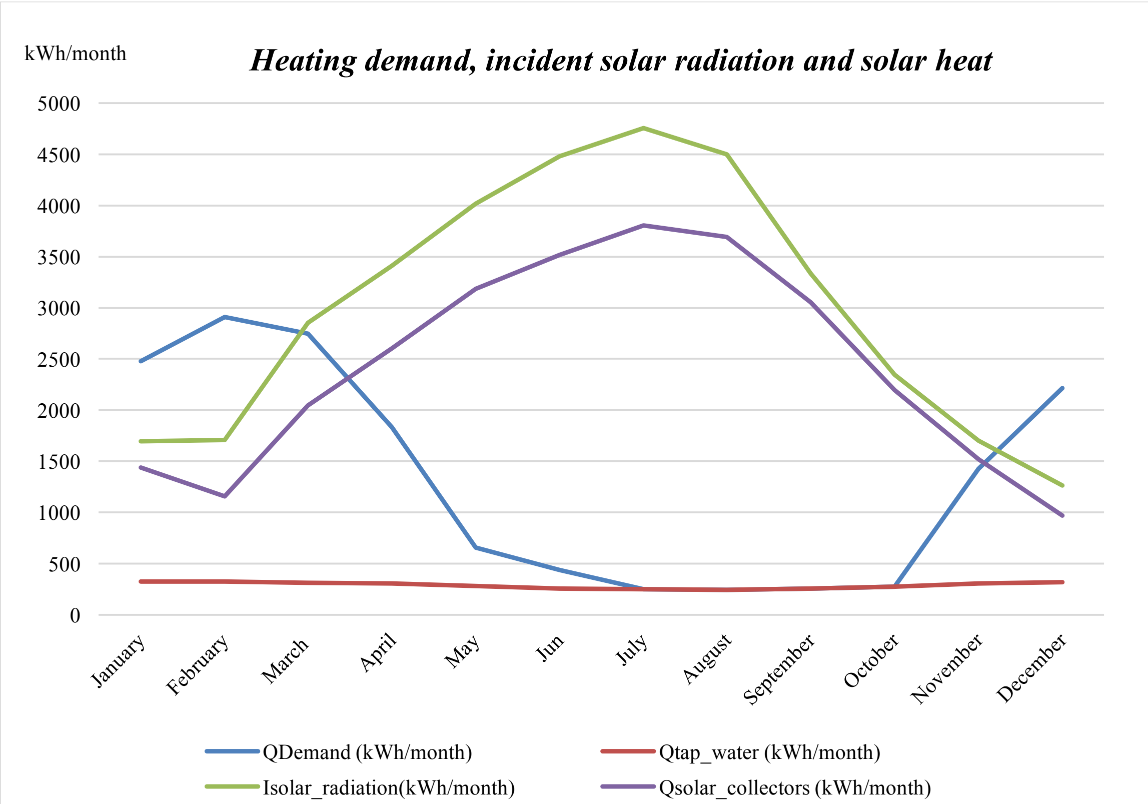

Figure C 1. Energy comparison between heating demand, tap water and solar gain by solar collectors