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Solar thermal energy storage for the typical European dwelling; available resources, storage requirements and demand

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Abstract

Thermochemical energy storage materials store heat at higher energy storage densities via reversible endothermic chemical reactions at ambient temperatures with lower thermal losses than sensible or latent energy storage systems. This research undertaken as part of the MERITS project, provides an estimation of the main requirements for domestic thermal energy storage from solar thermal collectors to meet thermal energy requirements (heating, cooling and hot water) for the mean European domestic dwelling (Floor area 98m^2) built to the regulations specified in 1999, 2012 and 2020, assuming that thermochemical energy storage systems could be effectively developed for seasonal storage of solar energy with a round trip efficiency of 75% from laboratory test results reported in the literature. The thermal energy demands of the mean European dwelling was calculated for three different climatic zones across Europe; Atlantic (Belfast UK), Continental (Berlin, DE) and Mediterranean (Murcia, ES) using the Meteonorm data set for a Typical Metrological Year (TMY). Solar collector performance was derived from proprietary designs of vacuum tube collectors assuming a mean system efficiency of 50%. It was estimated that currently only in Spain can a seasonal thermal energy store meet all the thermal energy demands of a dwelling (heating, cooling and hot water). However with a super insulated dwelling, using standards close to that of a Passivhaus (<15kWhm^{-2}yr^{-1}) thermal energy loads can be met with a reasonable area of solar thermal collector and storage volume for Atlantic and Continental climates.

1. Introduction

Across the European Union, (EU) buildings consume 40% of primary energy demands and the European Performance of Buildings Directive (EPBD) specifies that by 2020 new buildings need to have nearly-zero energy consumption. (Kalogirou, 2013). The UK's Climate Change Act requires the country to reduce carbon emissions to 20% of 1990 levels by 2050. Such requirements require substantial change to existing practice in the provision of heating, cooling and hot water in buildings. These comprise the bulk of energy use in buildings; in 2011 space heating in the UK accounted for 1.44 x 10^{12} MJ (26% of overall energy consumption), while water heating totalled 3.50 x 10^{8} MJ (Thompson, 2012). Space heating can be reduced through novel fabric and technology interventions, well insulated buildings with low levels of air infiltration, coupled with novel heating technologies such as solar energy systems and heat pumps reduce fossil fuel use for space heating demands. The PassivHaus concept of Wolfgang Feist requires a building design with a space heating requirement of ≤54 MJ m^{-2} yr^{-1} (≤15kWh m^{-2} yr^{-1}), with a total energy use ≤120kWh m^{-2} year^{-1} (432 MJ m^{-2}). For a 200 m^2 Passivhaus standard house, a space heating energy demand of ≤3000 kWh yr^{-1} (10.8 x 10^4 MJ) is substantially lower than the UK average of 14,400kWh yr^{-1} (5.2 x 10^4 MJ). The UK average dwelling floor area is 85m^2, needing 170kWh m^{-2} yr^{-1} (612 MJ m^{-2}) for thermal energy requirements. Across the European Union the average floor space of a dwelling is 98m^2 so for PassivHaus standards a maximum average space heating demand of ≤59976MJ must be achieved.

In urban areas solar collectors can be mounted on south facing rooftops, unobtrusively collecting solar radiation with proprietary designs having projected lifespans of 25 years. Thermochemical energy storage materials store heat via reversible chemical reactions with lower thermal losses than either sensible or latent

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energy storage materials but a practical application of this concept has not been achieved. Thermochemical storage materials have a potential storage density 15 times greater than water and 1 to 10 times greater than latent heat storage materials, (Abedin & Rosen, 2011) As such materials can store thermal energy at ambient conditions, losses are almost eliminated after cooling allowing longer term storage of solar energy for winter periods when irradiance levels are low and heating demands high. By investigating the boundary conditions and requirements of such systems, useful information is provided for the future deployment of technologies utilizing thermochemical reactions for seasonal solar thermal energy storage systems. Solar energy could be stored seasonally using larger collector arrays than present systems by storing any excess energy available after instantaneous demands are met, with a thermochemical storage vessel which due to higher energy densities would be useful for retro fitting to existing building stock to minimize reduction of living space.

Extensive reviews of solar thermal energy storage methods, materials and working examples have been reported by (Garg, et al., 1985), (Dincer & Rosen, 2002) and the latest state of the art review of solar seasonal storage undertaken by (Xu, et al., 2014). A review of a range of published literature on the round trip efficiency of thermochemical energy storage systems was undertaken to determine if there were any experimental studies detailing this. Abedin & Rosen, (2012) assessed a closed thermochemical thermal energy storage system investigating charging, discharging and storage, a round trip efficiency of 50% was reported. Lovegrove, et al., (1999) undertook an exergy analysis of amonia based thermochemical power systems. A thermal storage efficiency of 85% was attained but only 54.6% of this was recovered as useful heat. Lovegrove & Luzzi, (1996) reported that a maximum storage efficiency of 92% could be attained for an endothermic reactors utilising amonia based thermochemical energy storage.

Seasonal compact thermochemical energy storage is under investigation by the MERITS project (MERITS, 2014) for the European Union’s FP7 programme, to develop, demonstrate and evaluate a thermal battery based on novel high-density thermochemical materials. This system should supply up to 100% of domestic thermal energy loads; space heating, cooling and domestic hot water (DHW), via solar energy conversion devices using the following demand supply priorities, direct supply of heat when possible from the collectors, from the short to medium term sensible or latent energy storage system if needed, and finally from the thermal battery which is driven via a low grade heat source transferring the liberated heat from the reverse exothermic chemical reaction. Solar is proposed as the thermal energy source, as space in urban areas is at a premium with nearly 75% of the EU population inhabiting these, consuming 70% of Europe’s total energy requirements, (EU, 2012). In 2013) the total installed capacity of solar thermal systems within the EU was 30.2GW$_{th}$, (ESTIF, 2014).

Developing a thermal battery for existing dwellings with large energy loads is problematic, the area of solar collectors required prohibitively expensive and larger than the average area of a European house (this is demonstrated in the results and discussion section), hence the research currently being undertaken concentrates on development of a thermal energy storage and supply system for new dwellings or those retrofitted to almost Passivhaus standards. The overall objective of MERITS is to develop a thermal energy storage system capable of supplying up to 100% of thermal energy needs from renewable energy systems for dwellings constructed or retrofitted to near or Passivhaus standards. It must supply heat at various temperatures for different thermal energy loads as well as having a volumetric size that fits into domestic buildings or associated outdoor spaces limiting the size to ≤8m^3.

To develop such a system the MERITS project initially identified and estimated the likely boundary conditions for three different European climatic zones; Northern Maritime, Continental and Mediterranean, using metrological data sets from Belfast (UK), Berlin (DE) and Murcia (SP) to generate hourly weather conditions for each location. Storage materials, thermal energy storage capacity, storage sizing, solar collector array areas (A$_c$) and the associated control systems must be optimized before building a prototype for field testing using numerical simulation software such as TRNSYS. This work is currently being undertaken prior to constructing a prototype field test demonstrator (FTD) that could be used to develop such systems for market, stimulating manufacturing in Europe, reducing fossil fuel demands and help meet international agreements on reducing greenhouse gas emissions (EPA, 2010). Compact thermal energy storage systems would be subjected to a number of interrelated variables involved in collecting, storing and supplying thermal energy; as shown by figure 1.

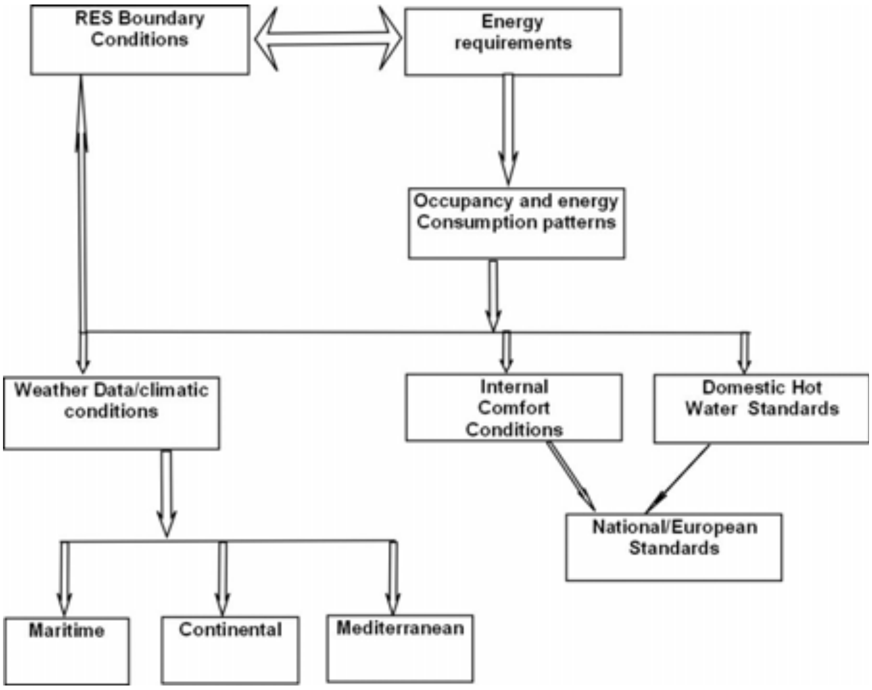

Figure 1 Schematic diagram of interrelationships between energy needs of consumers, renewable energy supply systems and the boundary conditions to which these are subject

Figure 1 demonstrates the interrelationships between the energy demands from end users, solar energy system performance, thermal energy storage, boundary conditions, European standards specifying particular performance requirements; for example DHW must be delivered at temperatures >56°C and thermochemical reactions require higher grade heat than that supplied to currently used aqueous sensible stores and perceived user thermal comfort (room temperature). As all of these factors are interrelated and impact on system design and hence performance the optimal situation must be identified for enabling the successful development of systems that can utilize thermochemical energy storage materials allowing their eventual deployment to market.

This research differs from previously published work in that it outlines the requirements and boundary conditions for developing successful thermochemical energy storage systems. This is achieved by modelling likely supply, solar radiation, and thermal energy demand scenarios created from degree-days and DHW requirements. Metrological data from three European sites has been used to determine degree-days. The demand scenarios are applied to a number of building types to providing information on how supply and demand scenarios differ according to climate and thermophysical building characteristics. The aim of this investigation was to determine the requirements needed to develop an effective thermochemical energy storage system storing thermal energy at higher storage densities (MJ m^{-3}), that could replace or augment conventional aqueous based sensibly-heated DHW storage tanks (4.178J $kg^{-1}K^{-1}$). The thermochemical energy store or *thermal battery* should have zero standing losses (WK^{-1}) as standing loses inhibit long term storage in sensible and latent energy storage systems. This would remove the mismatch between the availability and variability of solar radiation supply and thermal energy demands.

2. Methodology

Figure 2 depicts the TRNSYS model used to generate hourly weather data from the Meteonorm Typical Meteorological Years (TMY) database (Meteonorm, 2014) for Belfast (UK-Northern Maritime), Berlin (DE-Continental) and Murcia(SP-Mediterranean).

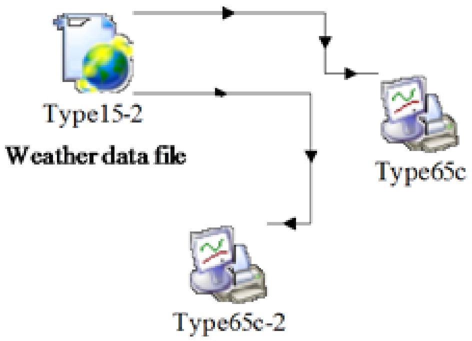

Figure 2 TRNSYS model used to generate weather data

The TRNSYS model shown in figure 2 generated hourly weather data (boundary conditions that the system was subject to) for; total incident solar radiation both diffuse & direct (MJ), mean ambient air temperatures (°C), mean wind speed (m s^{-1}) and Relative Humidity (%).

This was comprised of three TRNSYS sub components; one weather data file reader (Type 15-2 which can read and convert the TMY data) and two online graphical plotters to output the metrological data at a time step of one minute. This information was used to determine the optimum angle of inclination for maximising incident solar radiation on south facing surfaces. The optimum angle of incidence for a south facing surface in Belfast, Berlin and Murcia was found to be 40°, 40° and 30° respectively.

The collectors were inclined optimally at an angle of 40°, 40° and 30° and orientated due south for Belfast, Berlin and Murcia respectively to determine the input that could be expected from solar radiation Heating and Cooling Degree Days (HDD and CDD) using the procedure outlined in (Day, 2006) where calculated for each location from the meteonorm data sets to. European/National building regulations were then used alongside degree day values (Day, 2006), to estimate the thermal energy demand scenarios for the average European domestic dwelling (Floor area 98m^2), for the locations investigated, table 1 shows the surface area of each building element.

Table 1 Building element areas

Building element	Belfast (UK)	Berlin (DE)	Murcia (SP)
Roof area (m^2)	64	64	56.5
Walls (m^2)	129.64	129.64	129.64
Doors (m^2)	3.96	3.96	3.96
Windows (m^2)	12	12	12
Total (m^2)	209.6	209.6	202.1

From table 1 it is observed that the Murcia reference building has a smaller roof area than the other two, this is because roof pitch was set at the angle optimized for collection of solar energy at this location. The other two locations (Belfast and Berlin) had their roofs inclined at 40° as this was the value determined as optimal for collection of solar radiation using the TRNSYS model shown in figure 2. Different building standards from present (2014), previous (1999) and future (PassivHaus standard <54MJ yr^{-1}, <10Wm^{-2}) time periods, stipulated minimum values for the thermo-physical properties of building elements (Walls, Roof, Floor, Windows, Doors and Ventilation rates as total dwelling Air Changes per Hour (ACH)). These were used to calculate fabric and ventilation heat transfer rates allowing an overall building loss coefficient to be derived. Solar gain was not included in the calculations.

The Monthly thermal energy demands were determined from calculated degree-days (DD) and using the buildings' overall heat loss coefficient (UA), which was derived from the values shown in tables 1 and 2, see equation 1.

$$L_s = UA \times DD \tag{1}$$

DHW is independent of the size of dwelling, but is dependent upon the number of occupants and to a lesser extent, their behaviour. DHW usage was calculated using information from previous published research and the Meteonorm data sets. A study in the UK by the Energy Saving Trust (2008) measured hot water consumption in a number of dwellings. It found that an assumed temperature rise of 50°C was too high as it overestimates requirements, resulting in incorrect system sizing. Thermal gain from the building to the water supplied from the mains had been ignored by previous studies, which results in an over estimation of hot water needs, leading to the oversizing of hot water system. The other relevant point derived from this study is the measured mean cold water feed temperature, of 15.2°C, which is higher than the typically assumed mains water temperature of 10°C (EST, 2008)or 4.2°C higher than the mean UK soil temperature (NASA, 2000). A daily hot water consumption of 50 litres per person, was assumed (ECOHEATCOOL, 2006). The mean monthly energy demand for DHW for a typical EU household was estimated using equation 2, (Beckman, et al., 1977). Where L_W was the energy demand (J), C_p the specific heat capacity of water ($Jkg^{-1}\ K^{-1}$), V the volume of water heated (litres), N the number of days in the month, ρ the density of water and ΔT°C was the difference between the cold water feed and delivery temperature.

$$Q_{DHW} = C_p V \rho (\Delta T°C) \times N \times ocuppants \qquad \{2\}$$

Table 2 U-values applied to the modelled buildings

	U-value ($Wm^{-2}K^{-1}$)			
Element	Wall	Floor	Roof	Glazing
UK				
1999	0.45	0.45	0.25	3
2012	0.3	0.2	0.2	2
2022	0.1	0.1	0.15	0.8
Germany				
1999	0.45	0.45	0.25	3
2012	0.28	0.35	0.2	1.3
2022	0.1	0.1	0.15	0.8
Spain				
1999	1.73	2.34	1.12	5.77
2012	0.52	0.45	0.82	4
2022	0.1	0.1	0.15	0.8

Solar collector efficiency was modelled by assuming that an ETC was used with an annual system efficiency of 50%, (DGS, 2005). The derived weather data, supply of solar energy and the diurnal energy demands of the building allowed the quantity of thermal energy supplied to the thermal battery for each month of the year at each location to be estimated. Reported experimental laboratory results of thermochemical energy storage material efficiencies described in the introduction ranged from 50 to 92%. To estimate the quantity of useful solar energy that could be potentially collected, supplied and stored in the thermochemical material a round trip efficiency of 75% was assumed for estimating the quantity of energy that could be stored and discharged by the thermochemical storage unit.

3. Results

The methodology described in section 2 provided values for the boundary conditions to which the MERITS system would be exposed. Table 3 and 4 show the annual mean metrological and solar resource values respectively derived from the TRNSYS model shown in figure 2 and Meteonorm data sets for the locations under investigation. Table 5 provides the degree-days values for both heating and cooling of the reference building calculated using the method reported by (Day, 2006).

Table 3 Annual mean metrological conditions for locations investigated

Parameter	Ambient Temperature	Relative Humidity	Wind velocity
Location	(°C)	(%)	(m s^{-1})
Belfast (UK)	8.8	83.3	5.0
Berlin (DE)	9.4	73.1	4.5
Murcia (SP)	16.8	80.2	4.3

Table 4 Annual Solar Resource for three cities located in three different European climatic zones

Parameter (Unit)	Symbol	Belfast	Berlin	Murcia
Azimuth	γ	0	0	0
Surface tilt	β	40	40	30
Latitude	Φ	54.6	52.5	37
Solar irradiance (MJ m-2)	HI	3756	4161	7152
Beam irradiance ((MJ m-2)	Hb	1674	1940	4406
Diffuse Irradiance (MJ m-2)	Hd	2082	2249	2746

Table 5 Calculated Degree day data for locations investigated

Location	Climate	HDD	CDD
Belfast (UK)	Northern Maritime	2621	0
Murcia (SP)	Mediterranean	656	153
Berlin (DE)	Continental	2605	49

The annual solar resource available for the three locations investigated varied from, 3756 MJ in Belfast to 7152MJ in Murcia. The total annual solar resource available in Murcia (7152MJ) is higher than for Belfast (47.5%) and Berlin (41.8%) receiving about 57.5% of incident solar radiation as beam radiation, whereas Berlin and Belfast receive approximately 60% of the solar radiation from diffuse radiation. The degree-day values shown in table 6 demonstrate the different thermal energy needs of the reference building under different climatic zones. The northern maritime climate in Belfast requires no active cooling system, but has the largest requirement for space heating. Berlin has 16 fewer HDD than Belfast but has a cooling requirement necessitating the use of active cooling systems to maintain the thermal comfort of the building. Murcia has the highest requirement for cooling and approximately 25% of the HDD of the other two test locations investigated.

The annual thermal energy demand, the quantity of energy supplied by the collector array, the energy stored and the solar fraction for the nine different building scenarios were calculated as described in section 2 and shown in table 6. Taking into account the variation in the supply of energy from the solar collector, which has the ability to supply energy directly at certain times of the year, the model was configured to determine the total demand, total energy supply, the surplus energy after meeting concurrent demand and the total amount of energy that would need to be stored.

Table 6 Energy demands, supply, storage and solar fraction of the average European dwelling

Location	Belfast (UK)	Climate	Northern maritime
Year of building	1999	2012	Passivhaus
Energy demand (MJ)	49400	38000	17300
Collector area (m^2)	28	27.1	13
Collector input (MJ)	57900	45000	20900
Energy Stored	22100	16600	7100
Solar Fraction	0.62	1	1
Location	Berlin (DE)	Climate	Continental
Year of building	1999	2012	Passivhaus
Energy demand (MJ)	52900	41300	19400
Collector area (m^2)	28	27	13
Collector input (MJ)	64900	50.4	23400
Energy Stored	28900	22000	9800
Solar Fraction	0.69	1	1
Location	Murcia (SP)	Climate	Mediterranean
Year of building	1999	2012	Passivhaus
Energy demand (MJ)	29600	19700	10500
Collector area (m^2)	10.5	7	3.6
Collector input (MJ)	32700	21800	11200
Energy Stored	5900	4100	2000
Solar Fraction	1	1	1

As shown in table 6 a thermal battery and solar system cannot meet all the thermal energy demands for a Belfast house of floor area 98m^2 constructed to the building regulations stipulated in 1999 and for the house constructed in 2012 nearly the whole roof needs to be covered in solar thermal collectors. However a house proposed for construction in 2022 can supply all heating and hot water demands in Belfast with only 13m^2 of collector surface area. A house constructed in Belfast to the technical standards required in 1999 could only meet 62% of its thermal energy demands and for a similar house in Berlin 69% could be supplied. This implies that if 100% of thermal energy demands are to be supplied from renewable energy sources for older buildings then either the buildings fabric needs to be improved by retrofitting or an additional heat source is identified if buildings of this era are to be used.

The data presented has provided indicative values for the maximum amount of thermal energy that could be captured and utilised but has not considered losses from the pipe network, or the thermochemical store. The second law of thermodynamics means that no energy conversion process is ever 100% efficient. In the physical process under consideration a thermochemical reactor providing thermal energy will require energy to heat it to its required operating temperature as well as the energy lost when the reactants cool. To date (September 2014) the amount of actual experimental data available on the efficacy of thermo chemical storage is limited. This technology has the highest potential energy storage density but is at a lower stage of development compared to either latent or sensible thermal energy stores, (Muller-Steinhagen, et al., 2007) which can be bought in the market as proprietary products.

4. Discussion

After determining the energy requirements of a reference building situated in each of the three European climatic zones, it is clear that a different approach for each zone is required. During the winter in Belfast and Berlin (October to March) when space-heating demands are highest, solar radiation supply is minimal, (NASA, 2000). So northern maritime and continental climates would benefit most from inter-seasonal storage to provide sustainable space heating during the winter months, though the challenge is to store it with reasonable efficiency as well as at an economically viable cost. Mediterranean climates are fortunate in that their greatest energy demand (in this case for cooling) occurs when the solar resource is highest so longer term (inter-seasonal) storage is not as essential for these areas as it is for more northerly regions, but cold winters and variability of the solar resource can still occur in southern Europe.

From the calculated monthly thermal energy demands it was found that, currently only in Spain can a seasonal thermal energy store meet all the thermal energy demands of a dwelling (heating, cooling and hot water) for the building configurations investigated. For thermal battery to deliever the thermal energy demands of the average European dwelling in Belfast and Berlin then substantial reductions in space heating must be achieved, with domestic hot water as the main heating requirement.

5. Conclusion

If sufficient solar energy at a high enough temperature to initiate the required reactions could be collected annually to generate a solar fuel that could also be reused annually significant reductions in fossil fuels would be achieved. However this is only possible in northern Europe by significantly reducing space-heating demand and requires a significant roof area, leading to clashes with PV installations. Though if costs were competitive with other sources of thermal energy it could significantly augment the use of fossil fuels in older buildings. Success in achieving this is dependent on the effects of thermal cycling, efficiency, and durability of the storage chemicals used alongside associated control and containment systems under development. It has been demonstrated that theoretically it is possible to provide domestic thermal energy demands from solar energy using a seasonal store across Europe. The figures projected in this research use a round trip efficiency of 75% for the thermal battery. If the technologies being developed have significantly lower efficiencies then it would be difficult to deploy these systems in continental and northern maritime climates. Future work to be undertaken must consider the influence of this and quantify the impacts of lower storage efficiencies.

Another draw-back for the proposed system is the competition for roof space. The reduction in the unit cost of photovoltaic panels, and government promotional subsidies such as the UK feed-in-tariff, has led the rapid deployment of photovoltaics on domestic roofs in recent years, maximising electrical generation by utilising as much of the roof as possible. Traditional solar thermal systems have an area of 5m^2, (EST, 2012). The proposed collector area required to charge a thermal battery would require similar areas to those currently used for photovoltaic systems where nearly the whole roof area is covered by solar collectors. This then leads to competition between solar technologies, or highlights the development of better photovoltaic-thermal collector technologies. Though considering across the European Union, (EU) buildings consume 40% of primary energy demands such systems should be given serious consideration to help meet the targets set by the EPBD.

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