A Year in the Life of a Passive House with Solar Energy Store

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ABSTRACT

Due to a unique combination of factors, low energy and passive houses in Ireland are particularly well suited to exploiting the advantages of solar thermal energy. However few examples exist of how this synergy can be exploited successfully in Ireland, illustrating the manner in which sustainable fossil fuel-free space heating can be provided. This paper presents the design rationale and provides an overview of the performance of a real installation over a full year cycle. Key findings for this unique project are presented including (i) Design Criteria showing that that for the house under study, the heating season can be reduced from 10 months to 4 months using direct solar heating from a 10.6m^2 evacuated tube solar array, (ii) By storing excess solar energy, it has been demonstrated that the heating season was reduced by a further two months, (iii) Seasonal Store Mean Bulk Tank Temperatures, and associated soil Temperatures and Tank Losses and system Efficiency, (iv) Achieved Solar Fractions for DHW and Space Heating of 93% and 56% respectively and finally (v) Costs breakdown for the solar DHW, solar Space heating and Seasonal Energy Store summing to a total installed system cost for the sustainable solar heating system of €27,637.

INTRODUCTION.

There is significant potential afforded by solar assisted space heating in Northern maritime climates [1]. This reflects the fact that the usefulness of Solar Space Heating is a function of the amount of heating required and its pattern. Temperate maritime climates have a long heating season, coupled with mild winters and consequently a relatively high solar saving compared with countries with a continental climate which have a relatively short but high demand heating season.

As part of the EU funded CEPHEUS (Cost-Effective Passive Houses as EUropean Standard) project, 221 housing units complying with the Passivhaus standard were built in five European countries and their operation was evaluated. The project demonstrated that space-heating demand can be reduced to less than 15 kWh/(m^{2}a) through the application of the *Passivhaus* standard [2]. This represents a reduction of between 80 - 90% compared with the building regulations requirements pertaining at the time of the study.

Little attention has been paid to the optimisation of domestic hot water system efficiencies given the significant potential that existed heretofore for increasing space heating efficiencies. The *Passivhaus Planning Package* (PHPP) incorporates default assumptions, which already put the energy demand for domestic hot water higher than the 15 kWh/(m^{2}a) required for space heating [3]. However, recent analysis shows that the DHW demand may be significantly higher than that assumed in the PHPP as total typical UK demand for hot water ranges from 27 kWh/(m^{2}a) to over 40 kWh/(m^{2}a) [4]. This represents approximately twice the space heating demand of a house built to *Passivhaus* standards. Given the recent advances in building regulations standards introduced across Europe as part of the EU Energy Performance of Buildings Directive (EPBD), energy demand for domestic hot water is set to exceed energy demand for space heating across Europe for newbuild, as space heating energy demands approach those of the *Passivhaus* standard.

While passive solar techniques are typically used to reduce space-heating demand, solar heating of domestic hot water requires the integration of solar collectors into the domestic hot water system. Given falling prices of solar collectors, and the relatively high set cost of installation, excess solar collectors can be added at minimal extra cost. This can be used to significantly increase the solar fraction of domestic hot water, reducing the energy demand of a low energy or *Passivhaus* significantly.

Viability of seasonal thermal energy storage

Roth & Broderick [5] recognised the advantages of saving low-cost heat using a Seasonal Thermal Energy Store (STES). Applying the principle of storing low-cost surplus thermal energy from a domestic hot water installation, is it possible to supply the space heating needs of a *Passivhaus* located in Ireland through the use of an inter-seasonal store?

The most common seasonal thermal energy stores are Aquifer Thermal Energy Stores (ATES) and Borehole Thermal Energy Stores (BTES). However both of these require suitable ground conditions that do not always exist [6]. The size of STES is also important to consider, as efficiency and economic viability improve with scale [7]. This suits countries where community-based heating systems are common such as the Netherlands, which currently has the largest number of STES installations in Europe [5]. However, the largest proportion of houses built in Ireland are detached dwellings (54.2% and 45.7% respectively for 2010 and 2009, [8]. In addition, detached dwellings also often afford the advantage of providing sufficient land for the installation of a seasonal thermal energy store. Thus, for Ireland, consideration needs to be given to the single dwelling.

OVERVIEW OF INSTALLATION

Scandinavian Homes Ltd., a manufacturer of Passive Homes, built a Passive House of 215m^2 showhouse in Galway in 2006, see figure 1. The house has a very low space heating demand of 1827kWh (as determined by the Passive House Planning Package - PHPP), when it is used as a residence for a family of four. The house is currently used primarily as an office and show house, but also has periods when it is lived in. In June 2009, an underground aqueous Seasonal Thermal Energy Store was installed in order to showcase the possibilities afforded by the exceptionally low space heating demands of the *Passivhaus*. The system was to be used to supplement the electric space heating and lead to an increase in the solar fraction for the house.

The University of Ulster has gathered empirical data in order to supplement theoretical research in the area, monitoring the performance of the Seasonal Store installation. The data that has been gathered is being used to validate a computer model of the installation, which has been tailored to the Irish climate. This is being used to assist with scenario planning and in turn drive the optimisation of Irish Seasonal Thermal Energy Storage Systems, which is the subject of another paper.

Figure 1. Passive House with Solar Collectors and Seasonal Energy Store

An Evacuated Tube Solar collector array, of 10.8m^2 aperture, visible in Figure 1, collects diurnal heat and stores it indirectly in a 300 litre domestic hot water (DHW) cylinder (“Tank 1”) via a heat transfer coil, see figure 2. Once the temperature at the base of the DHW tank reaches 65°C, a three way valve diverts the solar heated fluid via a heat exchanger coil, to a subterranean Seasonal Store tank (“Tank 2”) of capacity 22,730 litres, which is located in the garden, see figure 3. The water in Tank 2 is not circulated and is used purely as an indirect sensible heat store.

DHW hot water for domestic use is drawn directly from the top of Tank 1, whereas the water in Tank 2 indirectly heats the domestic hot water supply and the space heating system via the underfloor and air duct heating systems. Due to the design employed, thermal stratification does not occur to any great extent in Tank 2, with the temperature difference between the top and bottom of the tank rarely exceeding 2°C. This arrangement ensures, a) the solar fraction for DHW is exceptionally high, and b) heat surplus to the DHW need is stored for winter use, ensuring the space heating Solar Fraction is increased. The cycle commences in February with the lowest tank temperature and finishes the following February once the summer solar energy has been captured and utilized over December and January.

DESCRIPTION OF MONITORING EQUIPMENT

The objective of the monitoring was to; a) determine key performance parameters such as solar fraction, solar yield etc for the installation, and b) examine means of improving the efficiency of the installation by investigating tank thermal stratification and thermal losses from the tank and pipework etc. In order to do this a total of 67 sensors were installed to monitor Tank 2 and its performance in relation to the space heating demand. In addition, basic information was gathered on other components, such as Tank 1, in order to provide a full picture of the energy balance and flows. Table 1 outlines the sensors and what they are used to assess.

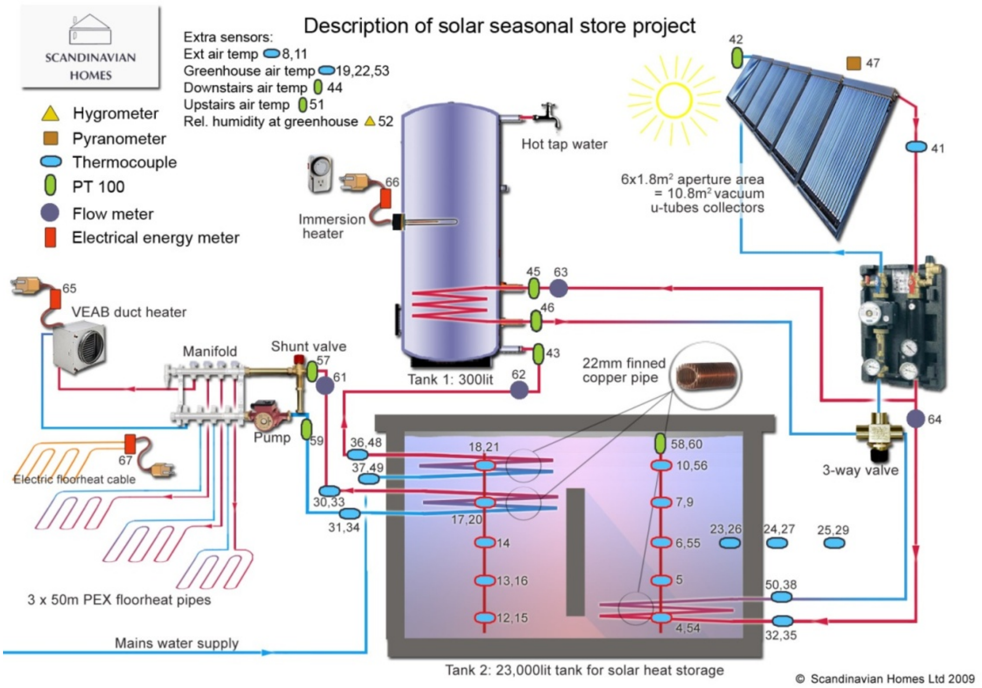


Figure 2: Schematic of the water system showing the position of sensors

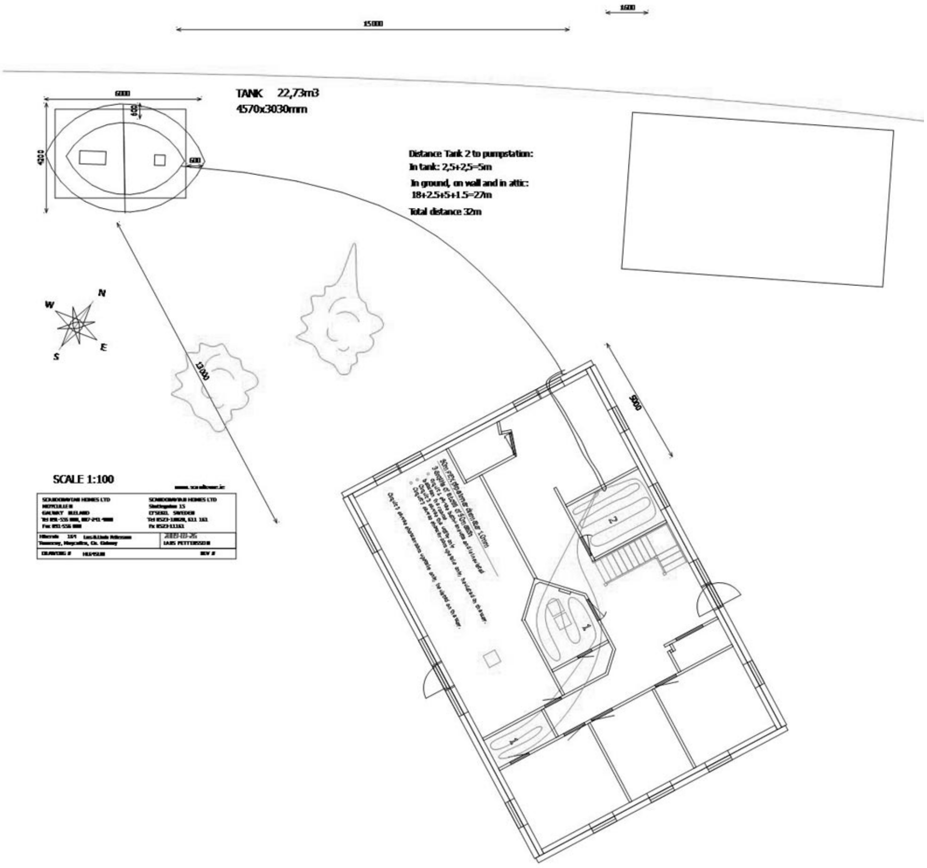


Figure 3. Location of the Seasonal Store and Underfloor Heating System Pipe Runs.

Table 1: The temperature sensors in the solar store circuits

1. the mean bulk tank temperature profile in tank 2.	Heat Loss Co-efficient for the Seasonal Storage Tank can be calculated
2. the thermal stratification within tank 2	
3. the surrounding soil temperature	
4. the temperature of the Flow and Return pipes to and from the tanks	the quantity of heat transferred to and from Tank 2 can be calculated
5. The quantity of Heat Transfer fluid flowing through the pipes	
6. The quantity of electrical energy used for DHW and space heating	the system efficiency and solar yield can be calculated
7. The environmental conditions to which the system is subject i.e. external and internal temperatures, solar radiation etc.	

Using the heat quantities for electrical and solar heat, the solar fraction can be calculated. Other items being monitored facilitate commissioning of the system and making recommendations for how to improve the installation.

T-type thermocouples, calibrated to an accuracy of ± 0.25°C, were installed in the seasonal energy storage tank at heights of 0.15m, 0.51m, 1.07m, 1.53m and 2.0m in order to determine the thermal stratification within the tank. In addition, PT 100s were used in applications, which required greater accuracy, with A Class PT100's providing 0.15% accuracy. Temperature measurements were made at the points indicated in figure 2 above.

Data from the installed sensors was sampled every 10 seconds, averaged and then recorded every 6 minutes using a multi channel logger, with data retrieved weekly via an Internet connection and downloaded to an off-site persistence layer. In excess of 10,000 individual data measurements were taken on a daily basis and amalgamated into a monthly spreadsheet from which the required calculations were made.

PREDICTED SPACE HEATING DEMAND

Figure 4 and table 2 below show the predicted space heating demand and the solar resource available from the 10.6 m² solar panels for the passive house built in Galway, Ireland. The figures are produced using the Passive House Planning Package and are tailored by using the efficiency figures for the solar collectors used on the site.

The heating season in Ireland is year around, with on average only 2 months not requiring heating. It can be seen from table 2 that the PHPP predictes a space heating requirement for this house in every month apart from July and August. By using the solar panels feeding the space heating directly, this heating season is reduced to 4 months.

Further, it can be seen that the total solar resource available from the 10.6 m² of solar panels is 4317 kWh, compared with the space heating demand of 1832 kWh. Thus there is a surplus of 2485 kWh available for use or storage on an inter-seasonal basis, And if stored efficiently could meet a significant part of the load from November to February.

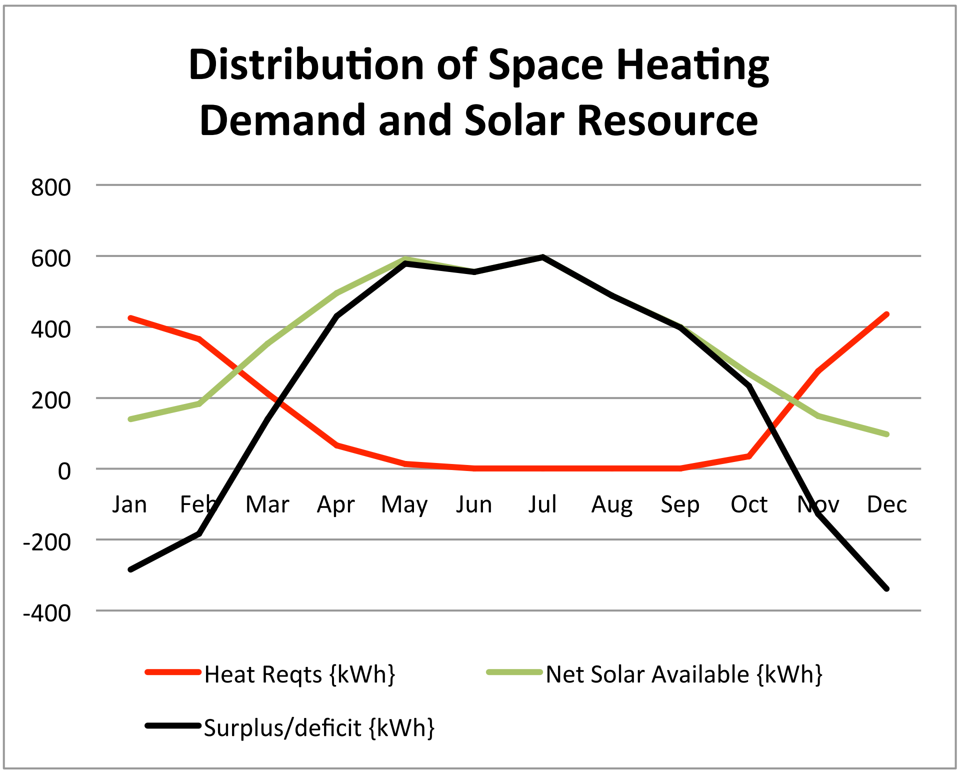
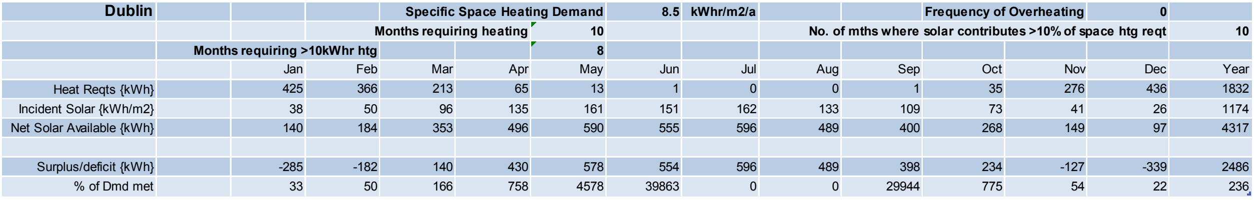


Figure 4 graph of predicted space heating demand and solar resource



Dublin				Specific Space Heating Demand			8.5	kWhr/m2/a			Frequency of Overheating		0	
			Months requiring heating			10			No. of mths where solar contributes >10% of space htg reqt					10
	Months requiring >10kWhr htg					8								
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Heat Reqts {kWh}		425	366	213	65	13	1	0	0	1	35	276	436	1832
Incident Solar {kWh/m2}		38	50	96	135	161	151	162	133	109	73	41	26	1174
Net Solar Available {kWh}		140	184	353	496	590	555	596	489	400	268	149	97	4317
Surplus/deficit {kWh}		-285	-182	140	430	578	554	596	489	398	234	-127	-339	2486
% of Dmd met		33	50	166	758	4578	39863	0	0	29944	775	54	22	236

Table 2 Predicted Space Heating Demand and Solar Resource for MOYCULLEN Passivhaus

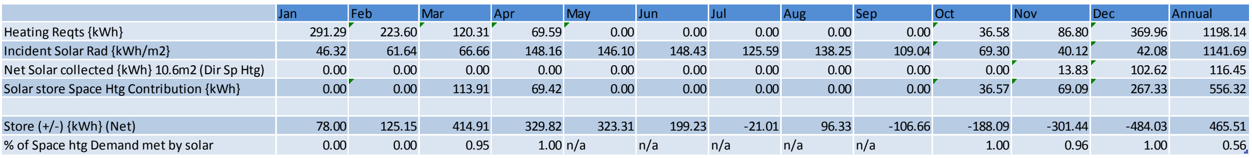
ACTUAL SPACE HEATING DEMAND & SOLAR FRACTIONS

The top row of table 3 shows that the space heating requirements for the passive house in Galway totalled 1198 kWh for the year. This is lower than the 1832 kWh predicted by the *Passivhaus* planning package, and reflects the usage as an office and show house rather than as a dwelling.

The domestic hot water demand throughout the year totaled 852 kWh, of which 793 kWh was met using the solar resource. This gives a domestic hot water solar fraction of 0.93, which is exceptionally high, but again the use of the house as an office must be considered.

PHPP predicts domestic hot water demand for such a house under normal occupancy of six people as 2968 kWh, with the solar contribution for the 10.6 m² of solar panels as 2539 kWh. This gives a solar fraction of 86%. Given that the figure of actual domestic hot water demand is significantly lower than the predicted domestic hot water use the further measurements under normal occupancy would ideally be done to verify the *Passivhaus* planning package predictions.

The recorded space heating demand for the year was 1198 kWh. Of this 556 kWh was met by the solar store, representing 46% of the space heating need. It can be seen from the table that the contribution from the solar store made in October, November and December decreasing the heating season by three months, The configuration of the installation was changed in November 2010 to allow heat from the solar panels to be distributed within the house through the heat recovery and ventilation (HRV) system. Table 3 illustrates that during the month of December (the first full month of operation of direct solar space heating), that of the 369 kWh space heating demand, 103 kWh was provided directly by solar. This gives a solar fraction for December of 28%, versus the predicted solar fraction as per figure 4 of 22% for the month of December. This close correlation between predicted and actual figures provide confidence in the forecasts inherent in table 2. Further monitoring of the performance of the system will be undertaken to gauge the effectiveness of direct space heating through the HRV System.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Heating Reqts {kWh}	291.29	223.60	120.31	69.59	0.00	0.00	0.00	0.00	0.00	36.58	86.80	369.96	1198.14
Incident Solar Rad {kWh/m2}	46.32	61.64	66.66	148.16	146.10	148.43	125.59	138.25	109.04	69.30	40.12	42.08	1141.69
Net Solar collected {kWh} 10.6m2 (Dir Sp Htg)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.83	102.62	116.45
Solar store Space Htg Contribution {kWh}	0.00	0.00	113.91	69.42	0.00	0.00	0.00	0.00	0.00	36.57	69.09	267.33	556.32
Store (+/-) {kWh} (Net)	78.00	125.15	414.91	329.82	323.31	199.23	-21.01	96.33	-106.66	-188.09	-301.44	-484.03	465.51
% of Space htg Demand met by solar	0.00	0.00	0.95	1.00	n/a	n/a	n/a	n/a	n/a	1.00	0.96	1.00	0.56

Table 3 Recorded heating demand, solar resource and space heating contribution from solar

ENERGY STORAGE CAPABILITY OF THE SEASONAL ENERGY STORE

The total energy capacity of the sensible heat store is given by

$$E = mc_p\Delta T \ \{\text{Joules}\} \qquad \text{eq 1}$$

where, E is the Energy in joules, m is mass, expressed in kg, c_p is the specific heat capacity, with units of J/kgK and ΔT is the temperature differential over which Q is being calculated.

Assuming that tank 2 can be heated to 85°C by the end of the summer and that the minimum useful temperature for the underfloor heating system is 25°C, the quantity of useful stored heat is;

$$Q = 22730 \text{ litres} \times 4.181 \text{ kJ/kg} \times (85 - 25)\ °\text{C} = 5.71 \text{ MJ or } 1586 \text{ kWh}$$

RECORDED MEAN BULK TANK TEMPERATURES

Figure 5 shows the recorded Mean Bulk Tank Temperatures (MBTT) at the site in Galway. The maximum temperature achieved was 67.1°C on 5 September 2010, and the temperature on 31 December was recorded at 23.7°C. These are lower than predicted due to user intervention and lower temperature rises and higher heating demand due to the climatic conditions experienced:

- Heat was drawn from tank two during the months of March (114kWh) and April (69kWh), providing 95% and 100% of the space heating needs respectively. The total resource drawn was calculated at 183kWh, equivalent to a reduction in the tank capacity of 215 kWh, given system losses of 17.6% (see section below). Considering that a rise in temperature of 1°C in tank two is equivalent to 26.4 kWh of energy, the temperature rise forgone due to this drawdown is in excess of 8°C.

- On 24 June, an ESB electricity outage occurred and the temperatures at the solar array exceeded 150°C, as the pump did not operate to draw the heat from the solar array. A leak was discovered on the roof on 25 June which required solar fluid to be topped up. The house was then left vacant until 25 August. Onside records are not detailed, but a system intervention was required on-site at the end of August. Following this, figure 5 shows that tank temperatures again started to increase.

- July was the dullest on record resulting in lower than anticipated sunshine and hence lower temperatures in tank two

- In November the lowest temperatures experienced since 1985 were recorded at most Irish Met Office locations, with some experiencing the lowest temperatures on record. Claremorris (the closest location to Moycullen) recording temperatures on average 1.3°C below normal.

- December experienced the lowest temperatures on record at most Met Office Locations with Claremorris (the closest location to Moycullen) recording temperatures on average 5.5°C below normal.

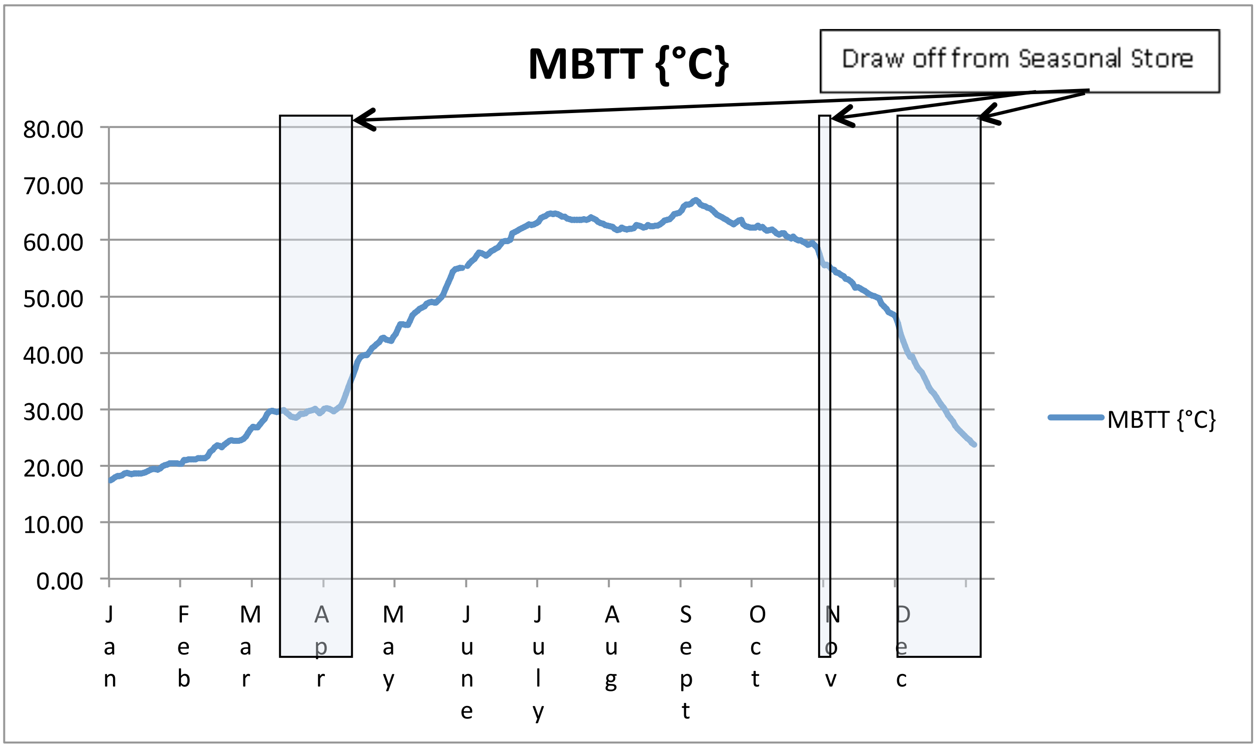


Figure 5 Mean Bulk Tank Temperatures Recorded

HEAT LOSS AND EFFICIENCY CALCULATIONS FOR THE SEASONAL STORE

Tanks losses form a significant factor in the performance of the Seasonal Energy Store, as can be seen from the forecast figures shown in Table 4 below. From the figures obtained from two cool down tests, the heat loss co-efficient U_z was calculated as 10 W/K. Using Eq 2 below the tank loss was calculated and the results presented in table 4.

Tank Loss = $\Delta T * U_z * 24 / 1000$ {kWh}, Eq 2

Where U_z is the heat loss causation, and ΔT *is the reduction in temperature*

Month	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
Ave MBTT {°C}	19.00	22.90	28.90	36.30	48.90	59.40	63.70	62.90	64.50	59.90	50.40	31.90
Soil Temp {°C}	6.10	8.00	9.10	11.30	14.60	18.20	19.90	20.60	19.60	17.80	14.10	9.70
Tank Losses {kwh}	92.88	107.28	142.56	180.00	246.96	296.64	315.36	304.56	323.28	303.12	261.36	159.84
Potential Daily Temp Loss {°C}	0.12	0.13	0.18	0.23	0.31	0.37	0.40	0.38	0.41	0.38	0.33	0.20

Table 4 Actual Heat Loss per month for 2010

The heat losses over the period of the year amount to 2744 kWh. The maximum peak useful heat stored in the Seasonal Store occurred when the store achieved 67.1°C, giving a usable range of 67.1°C - 25°C, or 42.1°C. At 26.4kWh/°C, this is equivalent to 1111.4 kWh. The efficiency of the seasonal thermal energy store, defined as the portion of heat transferred into the STES which remains available to meet loads is therefore:

Efficiency of STES = 465kWh/1111.4 = 41.8%

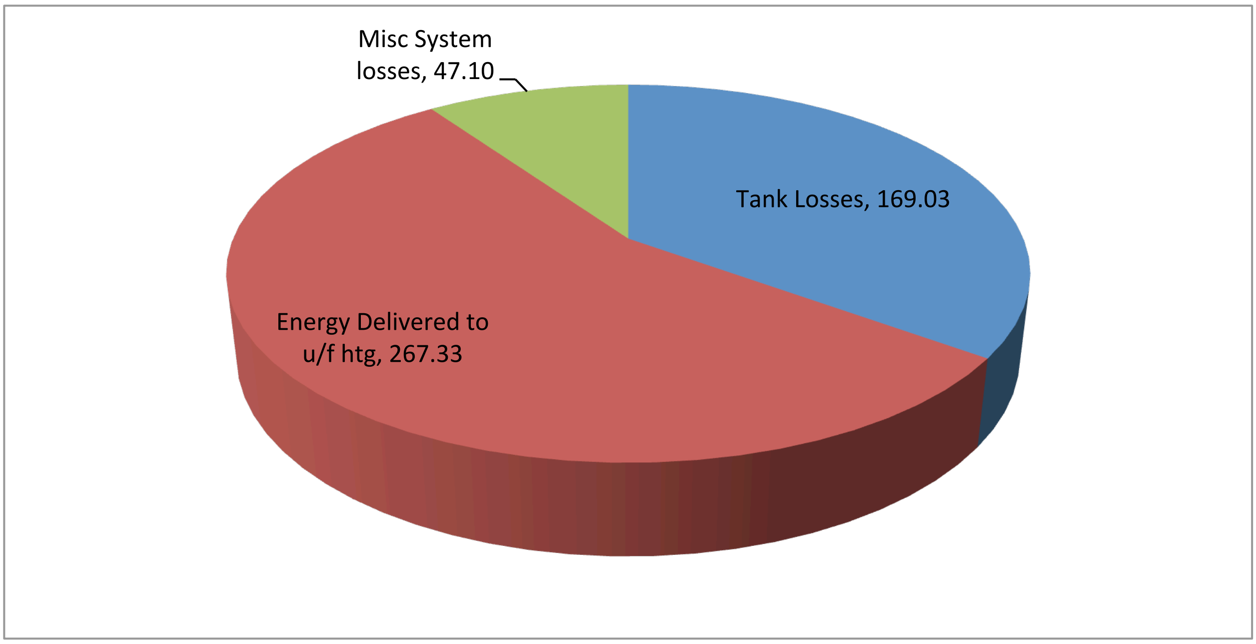


Fig 6 Breakdown of Energy Reduction of 483kWh in Tank 2 for December {kWh}

Figure 7 shows the breakdown of the energy reduction in tank two for the month of December. Tank losses amounted to 169kWh, while of the 267kWh delivered to the underfloor heating system, 47.1 kWh (17.6%) was lost through to system losses in transferring heat from the heat exchanger in tank two through the buried pipework to the underfloor heating system in the house.

SYSTEM COSTS

Table 4 below gives a breakdown of the total DHW and space heating system costs; the costs reflect all the components for the specific installation in Galway. In addition, for comparison purposes, the costs of an alternative fossil fuel system installation would need to be calculated including domestic hot water tank, oil fired burner, radiators along with all installation costs etc. The cost of the solar domestic hot water installation (4m^2 solar array coupled with a 300 L tank) is considered the base system, with an extra 6 m² of solar array and heat exchanger coil being added to the system in order to provide for solar space heating. Then the extra cost of a seasonal store is added on to storage surplus heat.

Item	Solar DHW	Solar Space Htg	Seasonal Store
	Total cost €	Extra Cost €	Extra Cost €
Parts	3057.00	3069.00	15042.30
Labour	3358.60	839.65	12594.75
Total	6415.60	3908.65	27637.05

Table 4 Costs of Solar DHW, Seasonal Store and Space Heating System

Many of the costs in table 4 would not be typical as they include:

- Installation of a greenhouse over the seasonal storage tank, along with steps to the greenhouse, wood chips on the ground etc in order to make the site suitable for customer visits
- Site specific tasks such as felling trees, chipping the wood etc.
- Research and development costs associated with the choice of materials, installation of non-standard insulation, customisation and configuration control circuitry etc.
- Installation of monitoring equipment along with associated installation of power and Internet connectivity etc
- In all, 75 man days was required, while it is estimated that less than 50 mandays would be required should the additional work specified above not be required.

Item	Solar DHW	Solar Space Htg	Seasonal Store
	Total cost €	Extra Cost €	Extra Cost €
Parts	3057.00	2269.00	11822.30
Labour	1679.30	559.77	8956.27
Total	4736.30	2828.77	20778.57

Table 5 Estimated Costs of Typical Solar DHW, Seasonal Store and Space Heating System

Table 5 above removes the extra non-typical costs associated with the installation, and presents a more realistic estimate.

Table 6 presents the estimated cost per delivered kilowatt-hour of energy under three different DHW usage scenarios. In the calculations, it is assumed that the domestic hot water and direct space heating installation will operate for 15 years, while the comparable lifetime for the seasonal storage tank was assumed to be 30 years. Capital costs were amortised using straight-line depreciation.

Under these assumptions, it is seen that the cost of domestic hot water heating ranges from €0.15 to €0.48, depending on the quantity of solar heat used. Similarly, the minimum cost per kilowatt-hour of heat used for direct space heating was €0.09 and the cost per delivered kilowatt-hour from the seasonal store ranged from €0.54 to €0.79.

Item	€ /kWh DHW	€ /kWh Dir Sp Htg	€ /kWh Seas Store	Ave €/kWh
Cost pa	382.42	55.25	692.62	1130.29
kWh Delivered (Scenario A)	2548.57	208.07	874.08	3630.72
Cost/kWh (€)	0.15	0.27	0.79	**0.31**
kWh Delivered (Scenario B)	792.36	614.58	1217.20	2624.14
Cost/kWh (€)	0.48	0.09	0.57	**0.43**
kWh Delivered (Scenario C)	1656.83	375.82	1279.51	3312.17
Cost/kWh (€)	0.23	0.15	0.54	**0.34**

Table 6 cost per unit of delivered energy based on three different DHW usage patterns, Seasonal Store depreciated over 30 years

The average cost per kilowatt-hour of delivered energy under the three DHW usage scenarios ranged from €0.31 to €0.43, with the most likely usage scenario C resulting in cost of delivered energy of €0.34.

The average cost of delivered energy at €0.34 is approximately twice that of the current cost of delivered electrical energy, although it is seen that by oversizing the solar array, very competitive costs can be achieved per kilowatt-hour of delivered energy for domestic hot water and direct space heating, even assuming that surplus energy is not used via the Seasonal Store.

In addition, it should be noted that the cost per kilowatt-hour is fixed based on a capital investment at today's prices, and will not be subject to volatile international energy markets.

CONCLUSION

The paper demonstrates the viability and potential of solar domestic hot water and space heating coupled with thermal seasonal energy storage when applied to low-energy houses in the Irish climate. The average cost of delivered energy achieved in the project ranged from €0.09c/kWh to €0.79c/kWh, with the thermal energy storage component proving the most expensive. By oversizing the solar array, an exceptionally high solar fraction of 93% was achieved for domestic hot water, while the addition of direct solar space heating reduced the heating season from 10 months to 4 months. A further reduction of two months in the heating season was achieved through the addition of the seasonal solar thermal energy store. The overall Space Heating Solar Fraction was 56%. While capital costs are high, the upward trend in the oil fuel price and carbon taxes increase should improve the economics of such installations of such systems in rural Ireland. Alternative thermal storage materials, with a larger heat capacity, are required to reduce the size of the solar store.

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