

# THE ROLE OF PROGRAMMABLE TRVS FOR SPACE HEATING ENERGY DEMAND REDUCTION IN UK HOMES

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## ABSTRACT

This paper aims to investigate the potential of advanced radiator controls to reduce space heating energy demand in dwellings. The study uses Dynamic Thermal Modelling (DTM) to compare the space heating energy consumption of dwellings with programmable Thermostatic Radiator Valves (TRVs) and dwellings with conventional TRVs. Conventional TRVs can often lead to overheating or heating rooms when not required. Programmable TRVs can overcome these limitations and this study employs DTM software package, DesignBuilder to estimate the resultant heating energy savings in a semi-detached dwelling. It is found that use of programmable TRVs can lead to space heating energy savings of up to 30%, without reducing thermal comfort of occupants.

## INTRODUCTION

Heating and cooling for providing thermal comfort have required human intervention since the first fire was lit in a cave. The Romans were among the first to use central heating systems instead of a simple open fire. In their central heating system, hot air produced from a wood fire flowed through under floor chambers (Meier and Walker, 2008).

The first oil crisis which occurred in 1973 urged the necessity for the first energy code (Building Energy Efficiency Standards). This code was established in 1978 in California and a part of it required the use of clock or set back thermostats for new homes. The main function of these thermostats was to save energy by automatically relaxing the temperature set points during night time when people were sleeping (Peffer et al., 2011). The oil price shock of early 1970s raised the interest in energy saving potentials of automated systems, while mostly comfort criteria had been considered before (Kastner et al., 2005).

Buildings are responsible for at least 40% of energy use in most countries in the world (WBCSD, 2007). In the UK, over 40% of energy is consumed in buildings. The energy consumed in homes is responsible for more than a quarter of CO<sub>2</sub> emissions (Energy Saving Trust, 2005). Carbon dioxide is the major cause of climate change and is also the main greenhouse gas produced by energy consumption in dwellings for which the government plans to reduce

the net UK carbon account for the year 2050 to at least 80% below the level of net UK emissions of 1990 (Climate Change Act, 2008).

People increasingly want to be comfortable in buildings. Control systems in buildings have the potential to improve occupant comfort level besides reducing energy consumption. Heating controls allow occupant to heat only the parts of their houses being used and reduce heating energy consumption of dwellings in this way. In fact, programmable room thermostats enable occupants to heat spaces when actually there are people in there (CIPHE, 2008). One important issue in using heating control is the time lag to heat the rooms to comfort temperature level. If the time lag to heat a new room is too high then it is likely that other rooms in dwelling may still get heating while they are unoccupied. This shows that, considerable amount of energy can be saved by effective control of heating systems and the right control is capable of reducing dwelling CO<sub>2</sub> emissions significantly.

Occupants can maintain the room temperature they want at different times by means of heating controls. This can be done either by programming heating systems and inputting occupancy schedules or turning the system on when cold and then use thermostatic control of heat output to achieve the desired temperatures. One popular way of controlling indoor air temperature by occupants is adjusting set-points. Set-point temperature schedules can operate the heating system according to user defined programmes during night, weekends or holidays (Vazquez and Kastner, 2010).

Study of literature showed that many modelling studies focus on different aspects of building performance according to the intent of study. However, not many take into account the details of heating systems such as the TRV control process and occupants' behavioural adjustment.

The main gap of the literature is that there is an ongoing debate about the effectiveness of new home technologies and more studies are required to investigate energy saving potential of these technologies. Although many studies have investigated the effect of change in heating set-points and efficiency of heating systems on energy demand reduction in domestic buildings, not many have

considered role of programmable TRVs as heating control devices on space heating energy consumption.

This work seeks to improve the literature in the area of energy saving potential of programmable TRVs by performing a modelling study producing a wide range of results. The aim is to explore the potential of advanced radiator controls for reducing day-to-day heating energy demand in UK homes. This study also aims to provide recommendations to occupants, house builders, government and manufacturers for the use of advanced radiator controls to maximise their heating energy saving potentials.

## METHODS

This study employs a DTM software package, DesignBuilder to estimate the heating energy consumption of a two storey; post World War II, semi-detached dwelling located in England. The heating system consists of a gas boiler, which distributes hot water through hot water loops to radiators in each room. Based on programmable TRVs capacities, possible scenarios for space heating are introduced and simulations are run to quantify reductions in total heating energy consumption of the dwelling. These cases include reducing heating set-points and heating time as well as turning off individual radiators when not required.

The simulation processing time and the time taken to analyse the results had to be balanced against the desire to cover as many dwelling types as possible. Considering time constraints of study, only one dwelling type was modelled. This dwelling type needed to be selected carefully so that it represents a good number of current dwellings in UK. Considering that a further experimental study can be performed to validate the results obtained in this study, it was decided to choose a building located in Loughborough. Hence, a semi-detached dwelling owned by Loughborough University was selected to be modelled.

### Building and Model Description

The modelled two storey building has a living room, main bedroom and kitchen which are located on the ground floor while other two bedrooms, a box room, bathroom and toilet are located on the first floor. The building of interest in this study is connected to another semi-detached building, which has same built type, construction details and floor plans. The front of building faces southeast and it has a pitched roof covered with concrete roof tiles. The building has wooden external and internal doors and windows are single glazed with painted wooden frame. External facade is covered with Red brick mainly and a single chimney way is provided. The building also has an insulated loft space, which has access from the first floor hall.

Living room has similar dimensions to bedroom 2 in first floor (4.2m×3.7m) and main bedroom has

similar dimensions to bedroom 1 in first floor (3.6×3.7m). Main bedroom and bedroom 1 have windows facing southeast while living room and bedroom 2 have windows facing north-west. The kitchen has access to the backyard through a glazed door on east wall and a window facing north-west. Bathroom and toilet are located near each other with high-level windows. The box room on the first floor is 4.4m<sup>2</sup> and has a window on the front wall of building. The height of all rooms in the building is 2.6m with a double height of 5.2m in staircase. Figure 1 shows the floor plan of the dwelling. These plans are generated from model geometry in DesignBuilder and show internal and external wall thicknesses as well. Internal walls are 0.1m and external walls are 0.36m thick.



Figure 1 Downstairs (left) and upstairs (right) floor plans

Building model is created in DesignBuilder software package and location is selected as East Midlands, UK but Birmingham weather data is used in simulation as it is the closest to the location of the building. The building has total area of 92m<sup>2</sup>, 13m<sup>2</sup> of which is not heated.

Materials used in construction of the building model are selected in accordance with the common construction materials used in semi-detached dwellings of 1940s. External walls consist of a layer of brick followed by 0.05m air filled gap, 0.1m mineral wool and 0.013m plaster board ( $U=0.45\text{m}^2/\text{K}$ ). Roof of the building consists of concrete roof tile followed by 0.1m mineral wool quilt and plasterboard ( $U=0.35\text{m}^2/\text{K}$ ). Internal partitions consist of single brick layer with plaster on each side ( $U=1.9\text{m}^2/\text{K}$ ). Windows are single glazed with painted wooden frame ( $U=3.7\text{m}^2/\text{K}$ ) and doors are wooden ( $U=2.8\text{m}^2/\text{K}$ ).

The building has a gas boiler, which provides hot water for both domestic hot water needs and radiators. Each zone of the building has a radiator, which works to meet the comfort criteria in the zone. Before assigning heating set-point to radiators in different rooms, boiler working hours are set. It is known that buildings are heated only for specific periods each day and boiler is turned off for the rest

of day. The Government Standard Assessment Procedure (SAP) suggests heating buildings from 07:00 to 09:00 and from 16:00 to 23:00 during work days and from 07:00 to 23:00 during weekends and holidays. However, study of literature shows that in reality; homes are heated for slightly a longer time each day. In HVAC part of dwelling model, heating systems (Boiler) is assumed to be working from 06:00 to 10:00 and from 16:00 to 24:00 during work days and from 06:00 to 24:00 during weekends and holidays to heat the building. This results in total of 4,692 working hours of the heating system throughout the year.

Heating set-points in various rooms are assigned for the dwelling model considering the thermal comfort criteria recommended by Chartered Institute of Building Engineers (CIBSE) guide A (CIBSE Guide A, 2006). It should also be mentioned that a heating set-back point of 12°C is also introduced in order to reduce freezing risk in dwelling and also avoid extreme heating energy requirement to heat the building back to comfort temperatures. This study assumes that each room has its own individual temperature control.

### Research Approach

This study investigates possible scenarios for space heating energy saving using programmable TRVs. These scenarios consider reduction in heating set-points and heating time as well as turning off individual radiators when not required. The main parts of this study are:

- **Study of base case model:** First part of the study looks into the base case model and tries to validate the simulation results obtained. Base case model does not consider any programmable

TRVs and assumes a conventional dwelling with radiators connected to boiler.

- **Impact of radiator controls on space heating energy demand:** Second part of the study investigates impact of radiator controls on space heating energy consumption and thermal comfort of occupants. In this part, it is assumed that dwelling has programmable TRVs and heating set-points can be altered when needed with fine precision.
- **Impact of heating time on space heating energy demand:** Finally, in the last part of the study, impact of reducing heating time on space heating energy consumption and thermal comfort of occupants is investigated.

## RESULTS AND DISCUSSION

As mentioned in previously, this study has three main parts and results are presented in three sections. First section presents overall annual results of base case model and validates these results by comparing them to national statistics and other studies in the area of domestic energy consumption.

### Base Case Model

Table 1 presents the floor area, annual electricity consumption, heating set-point, annual sensible heating load, annual heat loss and solar gain in each room and total annual gas consumption of the dwelling.

In Table 1, zone sensible heating is the amount of heat transferred from radiator to the room and the difference between total zone sensible heating demand and gas consumption shows the losses in boiler and hot water loop.

*Table 1 Floor area, heating set-point and base case simulation results (annual electricity and sensible heating energy demand, annual heat loss and annual solar gain in each room)*

Room Type		Area (m <sup>2</sup> )	Electricity Demand (kWh/yr)	Sensible Heating Energy Demand (kWh/yr)	Gas Demand (kWh/yr)	Set-point (°C)	Heat Loss (kWh/yr)	Solar Gain (kWh/yr)
Ground Floor	Main Bedroom	13.3	455	2,415	–	23	2,923	1,753
	Living room	15.5	882	2,626	–	23	2,961	1,650
	Kitchen	5.7	547	612	–	21	2982	842
First Floor	Bedroom 1	13.3	455	1,713	–	23	3,032	1,644
	Bedroom 2	15.5	530	2,141	–	23	3,106	1,376
	Bathroom	4.8	297	758	–	22	1114	256
	Toilet	1.0	191	114	–	21	307	41
	Box room	4.4	293	453	–	21	1386	810
Other (Halls)		5.5	499	0	–	–	2,085	693
Total		79.0	4,149	10,831	14,615	–	19,896	9,065

In other words, this difference is due to efficiency of heating system. Sensible heating in halls and staircases are zero because there is no radiator in these spaces. Heating set-points and heat losses are also given in this table to help understand the space heating energy consumption in each room. Heat losses are mainly due to infiltration and window openings.

The energy consumption break down shows 14,615 kWh of natural gas and 4,149 kWh of electricity is annually consumed in the building. Electricity consumptions shown for each room includes electricity used by appliances and lighting only and it does not take account for the electricity used by the boiler.

As can be seen in Table 1, living room requires the highest amount of sensible heating to maintain its comfort temperature. This can be related to large area of living room (15.5m<sup>2</sup>) which results in high heat loss from living room (2,961 kWh/year) and also high heating set-point of living room (23°C). Living room heating set-point is 2°C more than kitchen which results in considerable increase in space heating energy consumption of living room. Besides, living room faces north-west and receives less solar gain compared to south-east facing rooms. Simulation results show that solar gain in living room is 1,650 kWh/year which is less than solar gain in south facing main bedroom (1,753 kWh/year). Hence, it can be concluded that the difference in solar gain between living room and main bedroom is another reason for higher sensible heating load in living room (2,626 kWh/year) compared to main bedroom (2,415 kWh/year).

Main bedroom consumes the second highest sensible heating energy (2,415 kWh/year). Amount of sensible heating consumed in main bedroom is considerably higher than bedroom 1 (1,713 kWh/year). Considering that these two bedrooms have same heating set-points, floor area and almost the same heat loss and solar gain, the higher energy consumption in main bedroom can be related to the cooler ground floor hall due to presence of main entrance door. According to Table 1, ground floor and first floor halls have total heat loss of 2,085 kWh/year, 1,272 kWh/year of which is lost in ground floor hall (61%) and the remaining 813 kWh/year (39%) is lost in 1<sup>st</sup> floor hall. As a result, more sensible heating would be needed in main bedroom to compensate the effect of cooler neighbouring hall compared to bedroom 1.

Bedroom 2, consumes the third highest sensible heating energy (2,141 kWh/year) in the building. The higher space heating energy consumption in bedroom 2 compared to bedroom one can be related to larger area of bedroom 2 (15.5m<sup>2</sup>) compared to bedroom 1 (13.3m<sup>2</sup>) and also orientation of this bedroom. The window in bedroom 2 faces north-west which receive less solar gain compared to bedroom one which has a

window facing south-east. Simulation results show that solar gain in bedroom 2 is 1,376 kWh/year while solar gain in bedroom 1 is 1,644 kWh/year. There is 268 kWh/year difference in solar gains which provides a good reason for the difference in space heating energy consumption of the two bedrooms.

Other rooms like kitchen, bathroom, box room and toilet have relatively less space heating demand compared to living room and bedrooms which is as expected considering their smaller area and lower heating set-points.

Reducing space heating energy consumption is the main goal of this study but a special attention should also be given to thermal comfort requirements in the dwelling. It is important to maintain occupant's thermal comfort while trying to reduce space heating requirements of building. Simulation results show that almost all rooms meet thermal comfort criteria and no occupant discomfort is expected during winter. Figure 2 presents the hourly internal temperatures of occupied rooms during the coldest winter day (February 1<sup>st</sup>). It should be mentioned that February 1<sup>st</sup> is the weekday and during weekday, there are two heating periods as mentioned in Methods section.

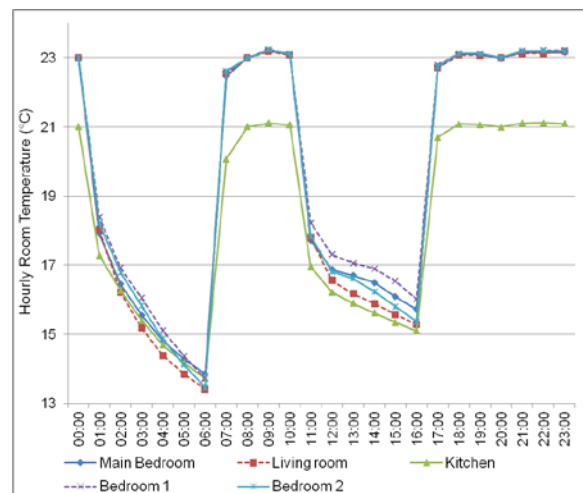


Figure 2 Hourly internal temperatures of occupied rooms during the coldest winter day (February 1<sup>st</sup>)

Figure 2 shows that during the coldest winter day internal temperatures can reduce to 13°C when boiler is off during night and reduce to 15°C when boiler is off during day. Knowing that occupants are either in bed or outside the dwelling, these temperature reductions are not expected to affect occupant's comfort. Figure 2 also shows that when boiler is on, comfort temperatures are maintained in all spaces considering heating set-points assigned to various rooms in the dwelling.

### Model Validation

To validate the results presented in Table 1, energy consumption of dwelling has been compared to national statistics and previous studies in the area of domestic energy consumption.

The UK Government's Department for Energy and Climate Change (DECC) publishes energy consumption statistics on the gove.uk website (DECC, 2013). These include domestic gas and electricity consumption data at the regional, local authority, medium and lower level super output areas. According to DECC, average annual gas consumption in UK dwellings is 16,906 kWh/year and average annual electricity consumption in UK dwellings is 4,198 kWh/year. DECC also provides dwelling energy consumption based on dwelling age and floor area. For dwellings built between 1946 and 1964, DECC suggest average annual gas and electricity consumptions of 16,484 kWh/year and 4,123 kWh/year respectively. For dwellings with floor area of 50-100 m<sup>2</sup>, DECC suggest average gas and electricity consumptions of 14,651 kWh/year and 3,949 kWh/year respectively.

DECC has been investigating the feasibility of developing a National Energy Efficiency Data framework (NEED) covering both domestic and non-domestic buildings. NEED provides the largest data source currently available for analysis of energy consumption at the building level. According to NEED database dwelling average annual gas and electricity consumption are 16,971 kWh/year and 3,474 kWh/year.

Comparison of simulation results for energy consumption of the dwelling model in this study with national statistics mentioned above, shows that dwelling gas consumption has great agreement with DECC statistics by floor area while electricity consumption of dwelling shows a good agreement with DECC statistics by age. Building energy consumption demand has the largest deviation from National Energy Efficiency Data framework (NEED) where gas consumption of dwelling is 13.9% more than NEED statistics and electricity consumption is 19.4% less than NEED data.

Results of other studies in the area of domestic energy consumption would also help to justify the simulation results of base case model of the dwelling. Various studies have investigated energy consumption in dwellings, which depending on their source of data and assumptions differ from each other to an extent. Firth et al. (2010) constructed a domestic energy model that classified dwellings according to their age and built form: 47 archetypes were constructed. Using data from the Meteorological Office, the 2001 Census, the English House Condition Survey, the Government Standard Assessment Procedure for Energy Rating of Dwellings (SAP) and the Building Research Establishment's Domestic Energy Model (BREDEM), they have found the average energy consumption for the main fuel types in UK dwellings. According to their study, average annual gas and electricity consumption in semi-detached dwellings are 17,727 kWh/year and 4,439 kWh/year respectively. Comparison of simulation results for

energy consumption of the dwelling model in this study with the study by Firth et al. (2010) revealed that the dwelling modelled here consumes 17.6% less gas and 16.2% less electricity. These numbers suggest that while having a good agreement with national statistics, our model underestimates gas and electricity consumption compared to other modelling studies.

Having compared simulation results to national statistics and the study by Firth et al. it is revealed that the average deviation of simulation results from different sources is 11% with minimum difference of 0.2% observed in comparison with DECC statistics based on floor area and maximum difference of 19.4% observed in comparison with NEED statistics.

### **Impact of Radiator Controls**

Two cases are studied here; first case investigates the impact of reducing heating set-points in whole dwelling and in an individual room on space heating energy consumption. Second case, quantifies the energy saving and percentage reduction in space heating energy resulted from turning off radiators in different rooms one by one.

In first part of first case, heating set-point in all rooms, at the same time, is reduced with 1°C steps up to 5°C while in second part, heating set-point in main bedroom, only, is reduced with 1°C steps up to 5°C and the reduction in total gas consumption of dwelling is quantified. Impact of reducing heating set-points on internal temperatures of mainly occupied rooms is also studied.

According to simulation results, 1°C reduction in heating set-point of whole house can lead to gas consumption saving of 16% annually. Another 1°C reduction in heating set-point would result in a further 16% and a total of 30% reduction in gas consumption of dwelling. Total gas consumption in a dwelling can be reduced up to 64% with 5°C reduction in heating set-point. However, decreasing heating set-point of whole dwelling beyond 2°C doesn't seem to be practical during cold winter days as this would result in reduced thermal comfort of occupants which is not desired. Hence, it would be helpful to look into impact of reducing heating set-points on internal air temperatures of mainly occupied rooms. However, it should be remembered that thermal comfort is assessed by subjective evaluation and that people understanding of their thermal comfort varies greatly. Hence, household that can tolerate lower room temperatures than standard values used in assessing the thermal comfort in this study, can achieve gas saving of up to 64% for space heating. Figure 3 shows the impact of reducing heating set-point on monthly average air temperature of occupied rooms in coldest month of year, February.

CIBSE guide A (2006) suggest a minimum winter operative temperature of 19°C for bedrooms, 21°C for living rooms and 17°C for kitchens in order to



maintain occupants comfort. Comparing room internal room air temperatures to thermal comfort criteria, it is realized that in bedrooms heating set-point can be reduced up to 2°C with no thermal discomfort and in kitchen up to 3°C with only a slight (0.2°C) difference with comfort temperatures. In living room, however, even a 1°C reduction in heating set-point results in decreased thermal comfort and further reduction in heating set-point may result in undesired thermal conditions.

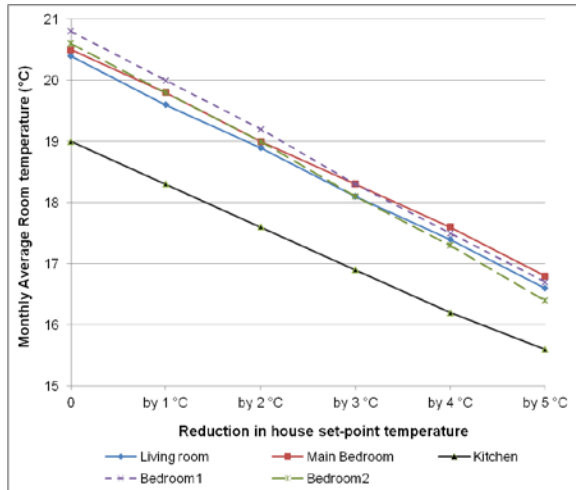


Figure 3 Impact of reducing heating set-point on monthly average air temperature of occupied rooms in February

Figure 3 shows that air temperature in all rooms decrease with decreasing heating set-point but with different slopes. The slope of line corresponding for Kitchen, for example, seems to be less than other rooms. This can be related to high amount of internal gain per unit floor area of the kitchen. High internal heat gain can compensate the effect of reducing heating set-point to some extent and the amount of decrease in room temperature with decreasing heating set-point is smaller, compared to other spaces.

In the second part of first case, heating set-point reduction is only applied to main bedroom. Simulation results showed that reducing heating set-point in main bedroom from 1°C to 5°C results in 4%-15% reduction in annual gas consumption of the dwelling. However, as for the previous part of the study, the limiting criteria for the amount of reduction in heating set-point of main bedroom is thermal comfort of occupants.

Studying the impact of reducing heating set-point in main bedroom on thermal comfort of occupants in dwelling, revealed that it can be reduced by up to 2.2°C which is slightly more than the case where heating set-points were reduced in all rooms at the same time (2°C). This slight increase in the possible set-point reduction can be related to the heat transfer from neighbouring and adjacent rooms, which experience no reduction in heating time or heating set-point.

In the second case, radiators in different rooms are turned off one by one and the reduction in total gas consumption of dwelling is quantified. Impact of turning off radiators on internal temperatures of mainly occupied rooms is also studied. Table 2 shows the total gas consumption of base case model and the resultant gas consumption of dwelling when turning off different radiators. This Table also includes the percentage reduction in gas consumption corresponding to each stage of turning off radiators.

Table 2 Simulation Results for whole house annual gas consumption and percentage reductions corresponding to turning off radiators in each room

Turning off radiator in	Floor Area (m <sup>2</sup> )	Total Gas consumption (kWh/year)	Reduction in Total Gas Consumption
Base Case	–	14,615	–
Main Bedroom	13.3	11,883	18.7%
Living room	15.5	11,781	19.4%
Kitchen	5.7	13,928	4.7%
Bedroom 1	13.3	13,135	10.1%
Bedroom 2	13.3	12,812	12.3%
box room	4.4	14,157	3.1%
Bathroom	4.8	14,011	4.1%

The amount of gas saving is dependent on room type and sensible heating required to maintain thermal comfort in the room. Hence, if a room is used for storage solely or is not occupied for any reason, turning radiators off in that room would lead to a gas saving of up to 19.4%. According to Table 2 turning off the radiators in living room, main bedroom and bedroom 2 have the greatest impact on annual gas consumption of the dwelling. This is in accordance with high sensible heating required in these spaces and with the large floor area of these rooms.

Turning off radiators for a long period rarely happens in real life as this would result in extremely uncomfortable thermal conditions in occupied zones. However, studying the impact of turning off radiators on space heating energy consumption gives idea about places where energy saving potential is high. For instance, bedroom 1 and bedroom 2 have same floor areas and heating set-point but bedroom 2 shows higher heating energy saving potential due to its orientation.

### Impact of Reducing Heating Time

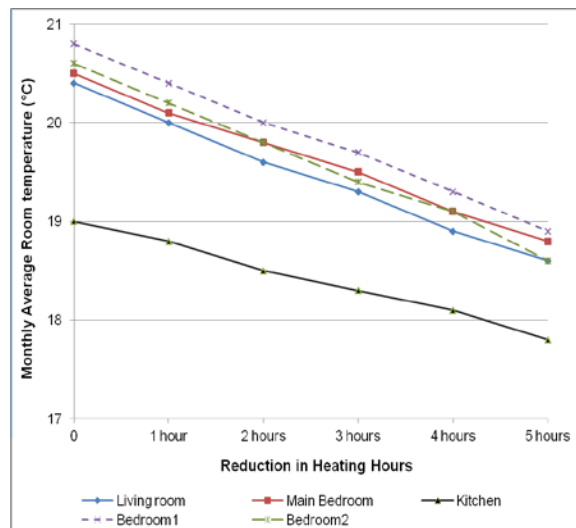
In the first part of this section, daily heating time in dwelling is reduced by 1 hour steps up to 5 hours

during both weekdays and weekends. This is done at the same time for all the rooms. Table 3 shows the simulation results for total gas consumption of dwelling after each stage of reducing heating time and compares the new gas consumption totals to the base case total gas consumption.

*Table 3 Simulation results for whole house annual gas consumption after each stage of reducing heating time*

Heating Time Reduced by	Total Gas consumption (kWh/year)	Reduction of Total Gas Consumption
0 hours	14,615	–
1 hour	13,766	5.8%
2 hours	12,779	12.6%
3 hours	12,110	17.1%
4 hours	11,331	22.5%
5 hours	10,540	27.9%

Table 3 shows that up to 28% reduction in total gas consumption can be achieved by reducing heating time and that only 1 hour reduction in daily heating time results in 5.8% total gas saving. However, it should be kept in mind that the limiting criterion for the length of reduction in heating time is the resultant impact on thermal comfort of occupants. Hence, it is necessary to look into internal air temperatures of rooms to make sure reducing heating time doesn't reduce the thermal comfort of occupants.



*Figure 4 Impact of reducing heating time on monthly average air temperature of the occupied rooms in February*

Figure 4 illustrates the impact of reducing heating hours on monthly average air temperature of mainly occupied rooms in February. Comparison of room air temperatures to thermal comfort criteria reveals that heating time in bedrooms can be reduced by up to 4.8 hours without having any negative impact on thermal comfort of occupants while no reduction in heating

time of living room is possible. The heating time in kitchen can be reduced beyond 5 hours without reducing thermal comfort of occupants.

Occupant's comfort is a limiting parameter in reducing heating time however, depending on occupancy type, occupants may spend more time in bed (like elderly occupants) when heating is not required. In these cases, heating time can be reduced further without having negative impact on occupant's comfort and gas saving of up to 28% can be achieved.

In the second part of this section, heating time reduction is only applied to the main bedroom. Simulation results showed that reducing heating time in the main bedroom from 1 hour to 5 hours results in 1%-6% reduction in annual gas consumption of the dwelling. It happens occasionally, especially in student houses, that one room is less occupied during a specific period (exams period for example, when student spend more time in library). In such cases, reducing the heating time of a single room can lead to gas saving of up to 6.2% for space heating. However, similarly to the previous part of the study, the limiting criterion for amount of reduction in heating time of the main bedroom is thermal comfort of occupants.

Studying the impact of reducing heating time in the main bedroom on thermal comfort of occupants in dwelling, revealed that heating time in the main bedroom can be reduced by up to 4.9 hours. This is half an hour more than the maximum reduction, which can be achieved in the main bedroom when heating time is reduced in all rooms at the same time. Hence, it can be stipulated that the heat transfer from neighbouring and adjacent rooms that experience no reduction in heating time enables the main bedroom heating time to be reduced for 30 more minutes. This accounts for 10% more reduction in heating time in the main bedroom, which results in 6% reduction in total gas consumption of dwelling.

## CONCLUSIONS

This study investigated the potential of programmable TRVs in reducing space heating energy consumption using Dynamic Thermal Modelling (DTM) software package DesignBuilder. Simulation results helped to study possible heating control strategies that can be achieved using programmable TRVs. It was found that use of programmable TRVs can lead to great space heating energy savings which cannot be achieved using conventional radiator controls. Using programmable TRVs, fine control of room temperature can be achieved which would help to reduce space heating energy consumption while maintaining occupant's thermal comfort. Furthermore, heating time can be controlled in individual rooms using programmable TRVs, which provide considerable space heating saving as revealed by the simulation results.

The following six main conclusions were achieved in this study,

Reducing heating set-point in a house across all radiators at the same time from 1°C to 5°C is shown to result in respective 16% to 64% reduction in annual gas consumption for space heating. Study of occupant's thermal comfort showed that it is impossible to decrease heating set-point in whole house up to 5°C without having negative impact on thermal comfort of occupants.

Turning individual radiators off, one at a time, is shown to result in a 3.1% to 19.4% reduction in annual gas consumption for space heating.

Reducing heating set-point in an individual room only (main bedroom in this study) from 1°C to 5°C is shown to result in 3.7% to 14.5% reduction in annual gas consumption for space heating. One of occupants may be willing to reduce heating set-point in his/her room more than the rest of house. Hence, by further reducing heating set-point in a single room of a house gas saving of up to 14.5% can be achieved.

Reducing heating time in all rooms of a house at the same time from one hour to five hours is shown to result in a 5.8% to 28% respective reduction in annual gas consumption for space heating.

Reducing heating time in an individual room only (main bedroom in this study) from one hour to five hours is shown to result in a 1.1% to 6.2% reduction in annual gas consumption for space heating.

Simulation results showed that bedrooms and kitchen have highest potential to reduce space heating energy consumption. When in bed, occupants tend to tolerate lower temperatures in bedrooms and heating set-point and heating time can be reduced further in the bedrooms. Kitchens, on the other hand, are not frequently occupied and usually cooking stove is on when occupants are in kitchen. Hence, further reduction in heating set-point and heating time of kitchens is possible.

It can be concluded from overall results that programmable TRVs are capable of saving space heating energy consumption in dwellings to a significant extent. Saving in space heating energy consumption varies greatly depending on type of control (reducing heating time or heating set-point) and controlled room (an individual room or whole house).

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Buildings through Digital Innovation (BuildTEDDI) funding programme. For more information see: [www.epsrc.ac.uk](http://www.epsrc.ac.uk) and [www.refitsmarthomes.org](http://www.refitsmarthomes.org)

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