OXFORD BROOKES UNIVERSITY

OISD Technology

Oxford Institute for Sustainable Development

Modern methods of construction and prefabrication

Sustainable building design
Construction and life cycle costing

Steel, concrete, timber, masonry and glass construction

Construction design guidance and regulation

Building physics including: thermal, acoustic, structural and airtightness testing and analysis

Building envelope systems
Product and systems development

CAD and computer modeling

Contact:
Prof. Ray Ogden

Report 090903ECC

Metal roofing on residential buildings in Europe: A dynamic thermal simulation study

Client

European Coil Coating Association

Oxford

September 2009

Author

Chris Kendrick

OISD Technology
Department of Architecture, School of the Built Environment, Oxford Brookes University, Gipsy Lane Campus Oxford OX3 0BP
Phone: +44 (0) 1865 483208, Fax +44 (0) 1865 483298, Email oisdtech@brookes.ac.uk
http://www.brookes.ac.uk/schools/be/oisd/act/technology/index.html!

Summary

Dynamic thermal modelling has shown that the choice of a metal or tile roof makes little difference to the thermal performance of housing across much of Europe, partly due to the level of thermal insulation used. A small difference is apparent in hotter climates where the thermal inertia of tiles leads to greater overheating, particularly in bedrooms. The ability to incorporate a heat-reflective coating in the metal roof made the difference even more apparent. Where a metal roof is used, cooling loads can be reduced if the house is air-conditioned, or hours overheating are decreased if no cooling is used.

Metal roofs can have a beneficial effect upon urban heat islands, particularly where solar reflective coatings are used, reducing both peak and average summertime surface temperatures during the day. All metal roof types will reduce heat stored in the building fabric which is a major contributor to urban heat islands.

1. Introduction

Metal roofs could replace conventional roof construction for many new-build and refurbishment projects across Europe. A metal roof could offer advantages in installed cost as well as the potential for reduction in cooling loads, particularly if solar reflective coatings are used. The main barriers to their use are resistance to unfamiliar construction techniques and planning restrictions, particularly relating to traditional building typologies.

A dynamic thermal simulation study was undertaken to compare the thermal performance of traditional tile roofs with metal roofs of the same U-value on a typical European house in four locations in Europe:

Strasbourg, France (48° 5' N)
Aix-en-Provence, France (43° 52' N)
Naples, Italy (40° 50' N)
Athens, Greece (37° 58' N)

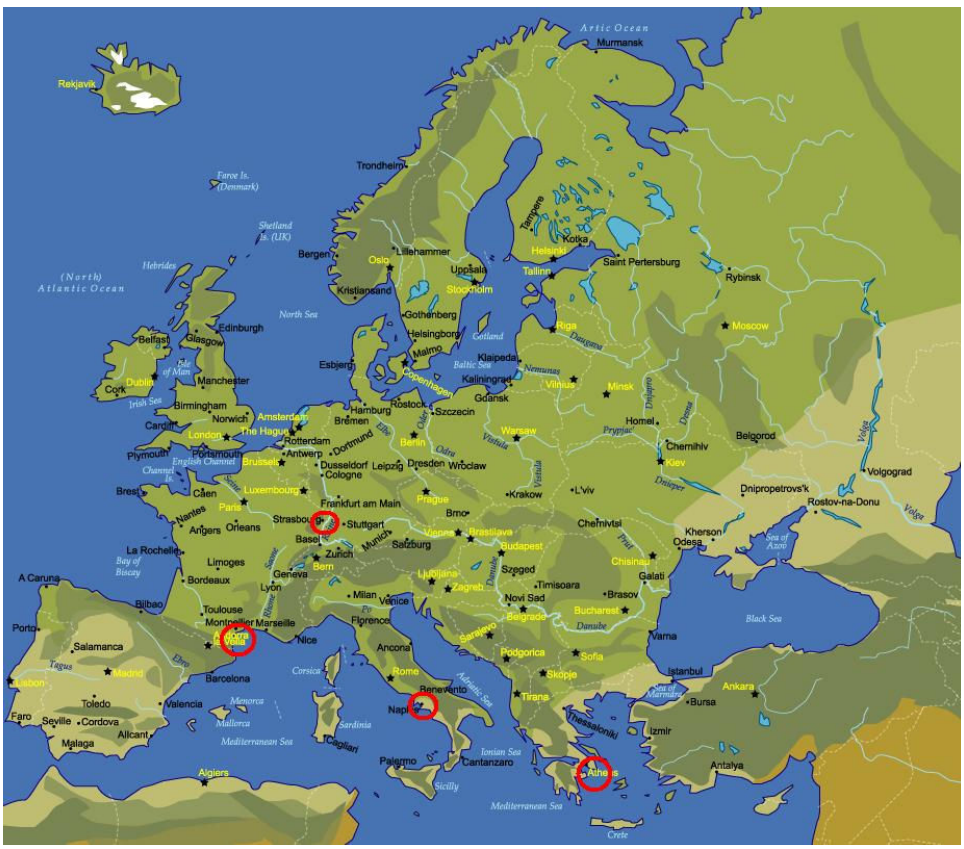


Figure 1. Location map

Insulation standards vary across Europe, loosely relating to climate, but also dependent upon individual country's building regulations and their emphasis upon energy conservation.

Country	U-value (W/m^2K)	Capital city	Latitude Deg N	Av deg C
Norway	0.18	OSLO	60.20	6.67
Finland	0.16	HELSINKI	60.10	5.00
Estonia	0.16	TALLINN	59.35	4.70
Sweden	0.13	STOCKHOLM	59.23	6.11
Latvia	0.20	RIGA	56.57	7.30
Denmark	0.25	COPENHAGEN	55.40	7.78
Lithuania	0.40	VILNIUS	54.63	6.11
Ireland	0.25	DUBLIN	53.20	10.00
Germany	0.20	BERLIN	52.31	8.89
The Netherlands	0.37	AMSTERDAM	52.30	10.00
Poland	0.30	WARSAW	52.13	7.70
United Kingdom	0.25	LONDON	51.30	10.56
Belgium	0.40	BRUSSELS	50.52	10.56
Czech Republic	0.30	PRAGUE	50.05	7.78
N France	0.20	PARIS	48.52	10.56
Austria	0.25	VIENNA	48.12	10.00
Slovakia	0.30	BRATISLAVA	48.09	9.90
Hungary	0.25	BUDAPEST	47.43	9.70
Switzerland	0.30	ZURICH	47.22	8.89
Slovenia	0.25	LJUBLJANA	46.22	9.50
N Croatia	0.65	ZAGREB	45.48	11.40
N Italy	0.43	MILAN	45.27	11.67
Serbia and Montenegro	0.65	BELGRADE	44.48	11.70
Romania	0.50	BUCHAREST	44.25	10.00
S Croatia	0.75	SPLIT	43.53	17.00
Bosnia-Herzegovina	0.55	SARAJEVO	43.52	9.50
N-Mid Italy	0.46	FLORENCE	43.50	14.60
S France	0.25	MARSEILLE	43.45	15.00
Bulgaria	0.30	SOFIA	42.41	10.50
Macedonia	0.65	SKOPJE	41.96	12.40
Albania	0.38	TIRANA	41.33	15.00
N Spain	0.41	BARCELONA	41.28	16.00
Mid-Italy	0.55	NAPLES	40.50	15.50
Mid Spain	0.38	MADRID	40.26	13.89
S Spain	0.45	VALENCIA	39.29	20.00
Portugal	0.50	LISBON	38.46	16.67
S Italy	0.60	PALERMO	38.09	18.50
Greece	0.50	ATHENS	37.96	17.78

Table 1. Insulation standards (roof U-values) across Europe. Source: European Insulation Manufacturers Association, EURIMA

From this table, two graphs were prepared to relate U-value requirements to both latitude (how far north) and average annual temperature.

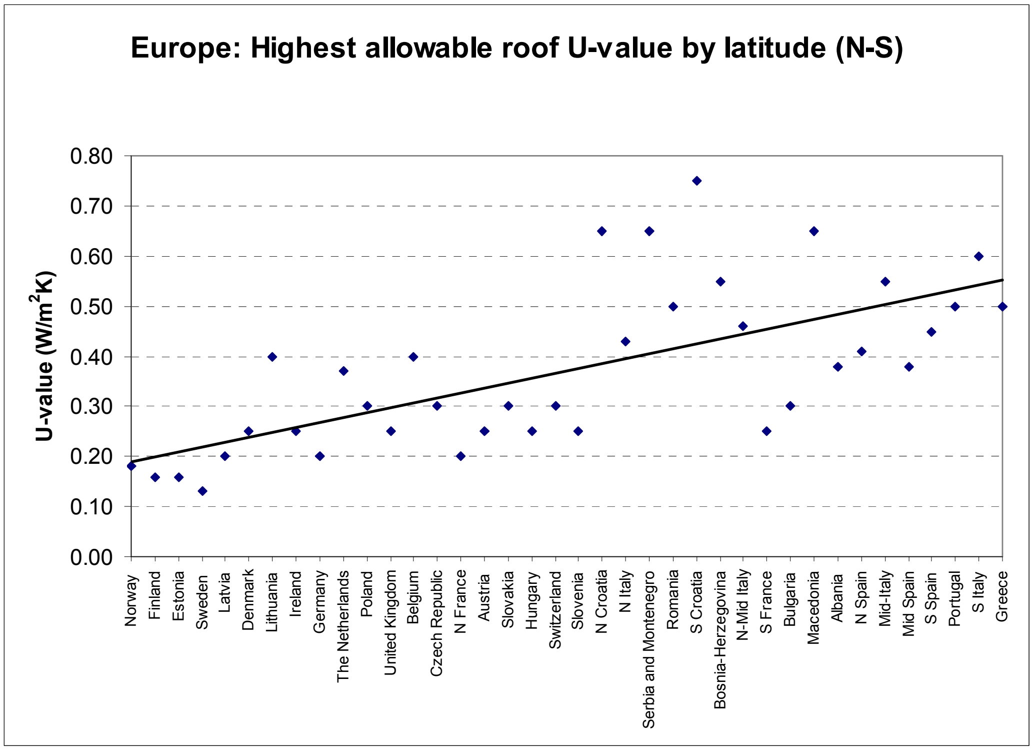


Figure 2. U-value related to latitude of city

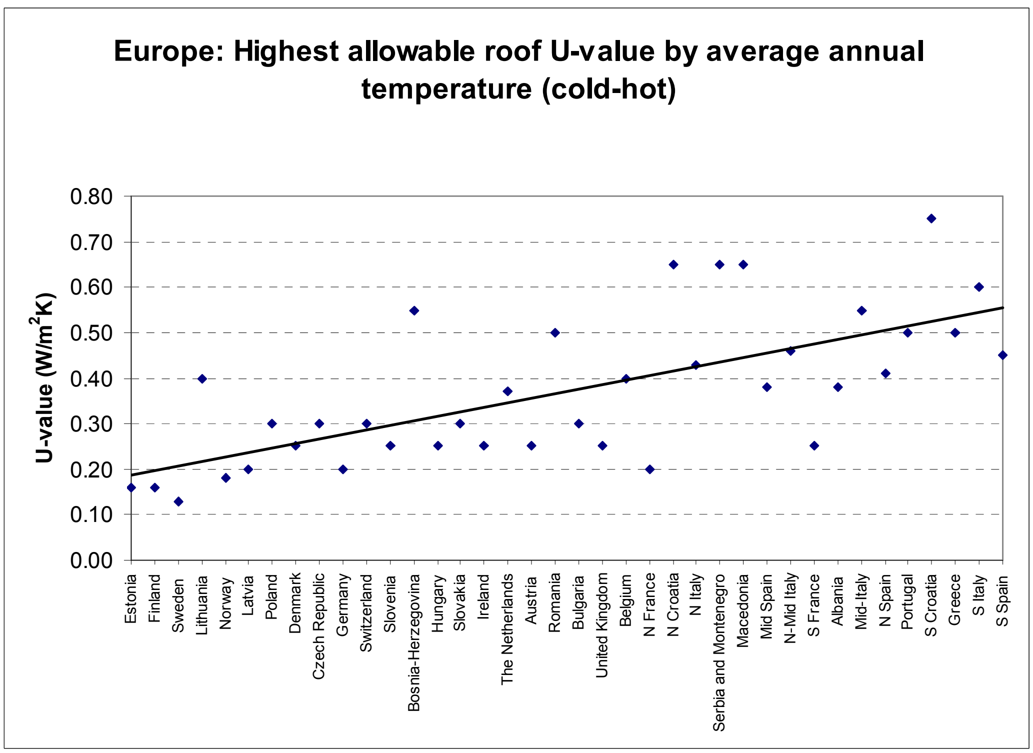


Figure 3. U-value related to average annual temperature

It can be seen from Figures 2 and 3 that U-values are generally higher the further south and the warmer the climate becomes.

The situation in countries such as France, Spain and Italy is complicated by the fact that they straddle different climatic regions. There are thus different U-value requirements across the country depending upon latitude, as shown for the example of France in Figure 4.

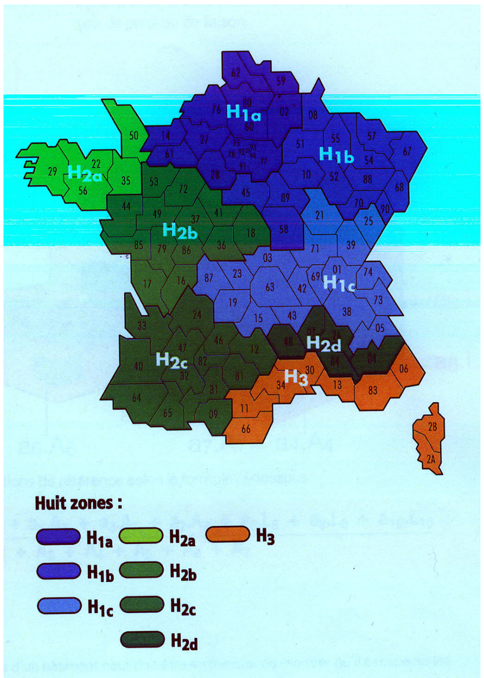
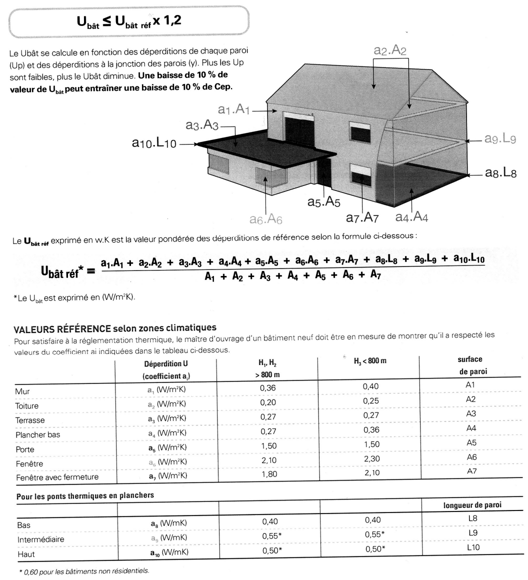


Figure 4. French climatic regions



$U_{bât} \leq U_{bât\ réf} \times 1{,}2$

Le Ubât se calcule en fonction des déperditions de chaque paroi (Up) et des déperditions à la jonction des parois (y). Plus les Up sont faibles, plus le Ubât diminue. **Une baisse de 10 % de valeur de $U_{bât}$ peut entraîner une baisse de 10 % de Cep.**

Le **$U_{bât\ réf}$** exprimé en w.K est la valeur pondérée des déperditions de référence selon la formule ci-dessous :

$$U_{bât\ réf}^{*} = \frac{a_1.A_1 + a_2.A_2 + a_3.A_3 + a_4.A_4 + a_5.A_5 + a_6.A_6 + a_7.A_7 + a_8.L_8 + a_9.L_9 + a_{10}.L_{10}}{A_1 + A_2 + A_3 + A_4 + A_5 + A_6 + A_7}$$

*Le $U_{bât}$ est exprimé en (W/m²K).

VALEURS RÉFÉRENCE selon zones climatiques

Pour satisfaire à la réglementation thermique, le maître d'ouvrage d'un bâtiment neuf doit être en mesure de montrer qu'il a respecté les valeurs du coefficient ai indiquées dans le tableau ci-dessous.

	Déperdition U (coefficient a_i)	H_1, H_2 > 800 m	H_3 < 800 m	surface de paroi
Mur	a_1 (W/m²K)	0,36	0,40	A1
Toiture	a_2 (W/m²K)	0,20	0,25	A2
Terrasse	a_3 (W/m²K)	0,27	0,27	A3
Plancher bas	a_4 (W/m²K)	0,27	0,36	A4
Porte	a_5 (W/m²K)	1,50	1,50	A5
Fenêtre	a_6 (W/m²K)	2,10	2,30	A6
Fenêtre avec fermeture	a_7 (W/m²K)	1,80	2,10	A7
Pour les ponts thermiques en planchers				
				longueur de paroi
Bas	a_8 (W/mK)	0,40	0,40	L8
Intermédiaire	a_9 (W/mK)	0,55*	0,55*	L9
Haut	a_{10} (W/mK)	0,50*	0,50*	L10

** 0,60 pour les bâtiments non résidentiels.*

Figure 5. U-values in France

2. The model

Extensive research was conducted on residential construction standards in various European locations. Whilst there are differences relating to traditional construction types, climate and material availability, it was evident that these could be simplified to a single model house which would be capable of accurately simulating the effect of changes in roof type. In assessing the roof, the model focussed on an upper-storey bedroom with a warm roof construction, i.e. with a ceiling which follows the slope of the roof.

A model was developed in IES TAS simulation software of a typical masonry house with U-values for all elements as specified in national requirements. The roof was sloped at 40 degrees, and an upper bedroom was created in the roof space. The metal roof construction simply used metal sheet instead of clay tiles. Solar reflectivity was initially set as 0.3 for both (clay red and medium grey), but a reflective metal coating (solar reflectivity 0.7)) was also trialled. Further details are given in the table below:

Model attribute	**Value/description**
Heating setpoint	16°C (bedrooms; 22°C living areas
Heating on/off	0600-0900; 1600-2300 (weekdays)
	0600-2300 (weekends)
Cooling setpoint	20°C in bedroom
Cooling on/off	As heating, bedroom only
Ventilation (when no cooling used)	Opening windows: user-controlled to open at 22°C outside heating season

Table 2. Tas model

Roof construction was assumed to be made up of layers (ignoring any framing elements). The same model was used for all four climates studied; changing roof and wall U-values to reflect local requirements (see Table 1).

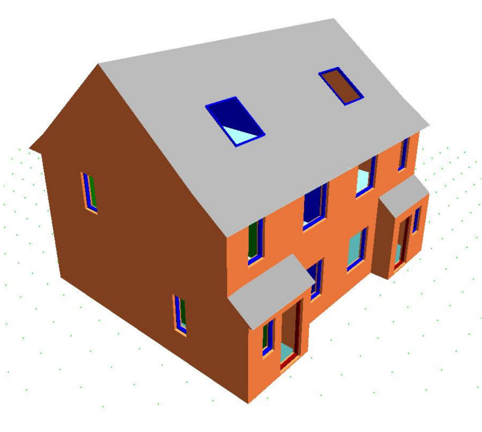


Figure 6. Tas model

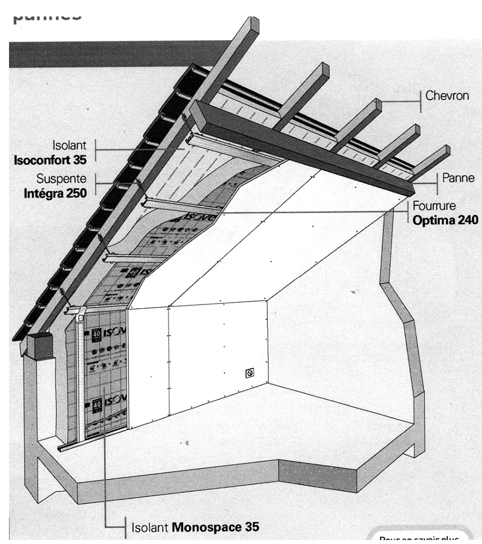


Figure 7. Typical roof construction

3. Results

3.1 Strasbourg: roof U-value 0.2W/m^{2}K

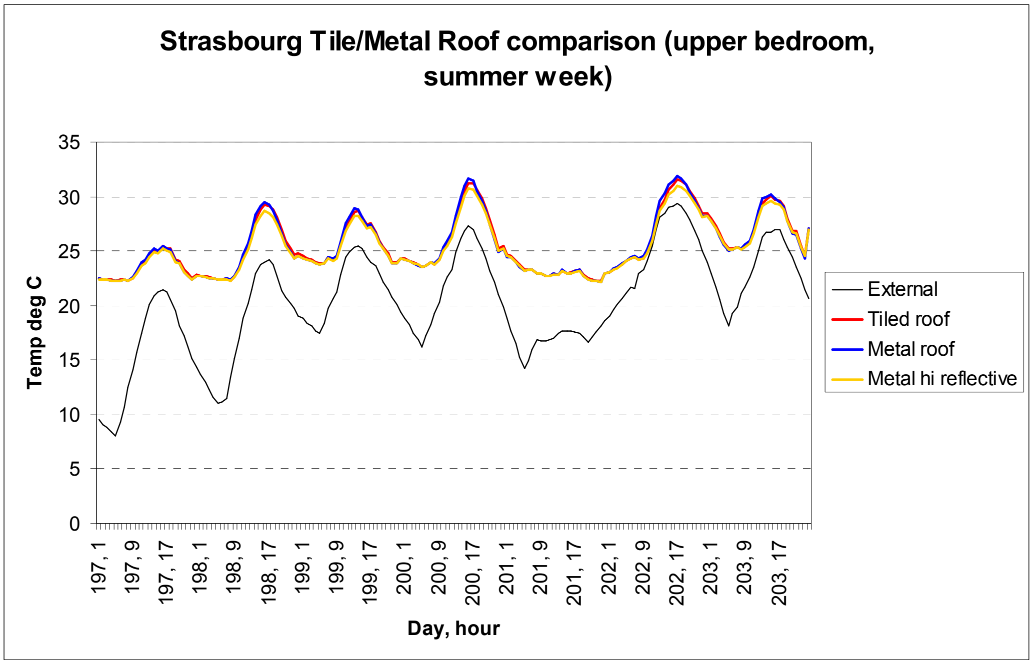


Figure 8.

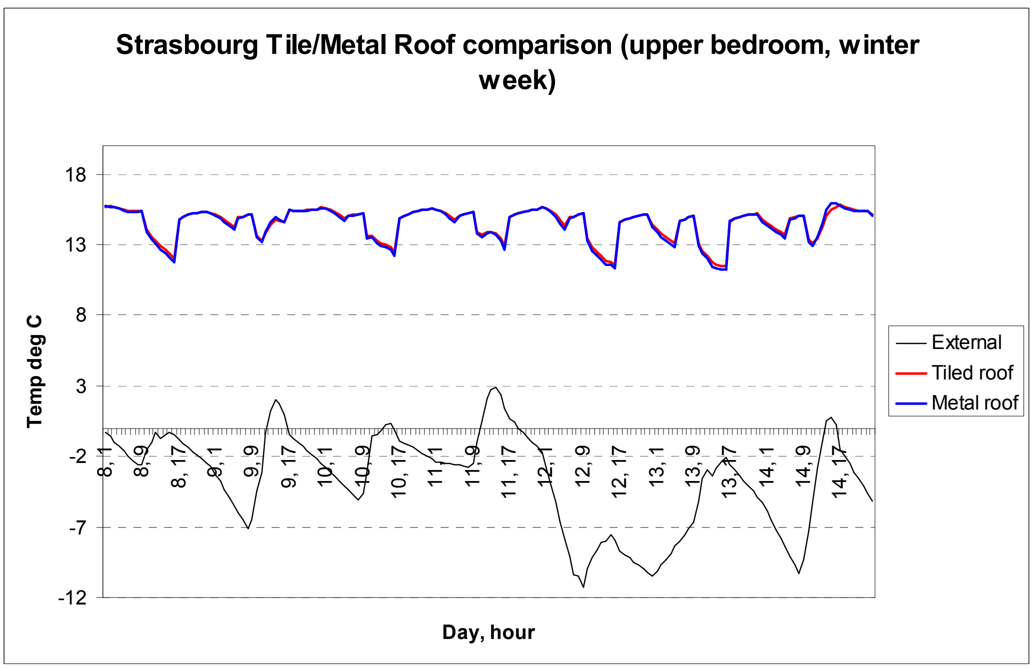


Figure 9.

There is little difference between the calculated dry resultant temperatures in the upper bedroom for any roof type.

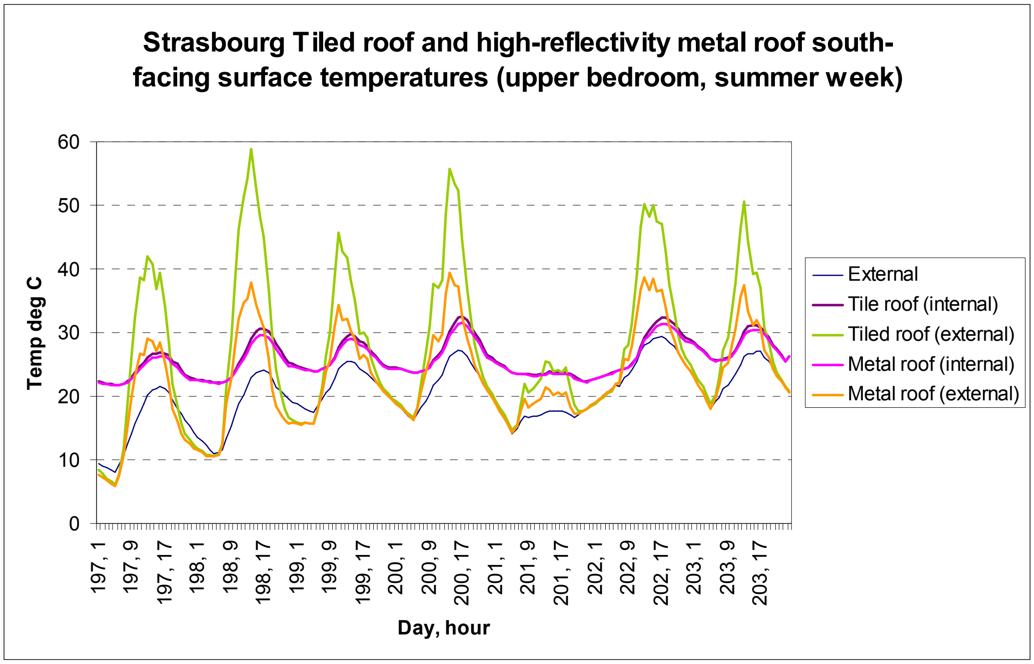


Figure 10.

The high reflectivity metal roof reduces external surface temperature considerably but internal surface temperatures are similar due to the insulation.

Values in kWh

Month	Heating (metal)	Heating (tile)	Heating (hi refl metal)
1	94.53	93.91	95.53
2	52.67	51.00	53.25
3	17.24	15.86	17.85
4	1.22	1.08	1.17
5	0.00	0.00	0.00
6	0.00	0.00	0.00
7	0.00	0.00	0.00
8	0.00	0.00	0.00
9	0.00	0.00	0.00
10	3.83	3.09	3.77
11	39.07	37.03	39.34
12	84.99	84.21	85.62
Total	293.55	286.19	296.54
Peak	1.18	1.20	1.21
Day	359	359	359
Hour	17	17	17

Table 3. Strasbourg heating loads (upper bedroom)

There is a very small heating increase with the metal roofs.

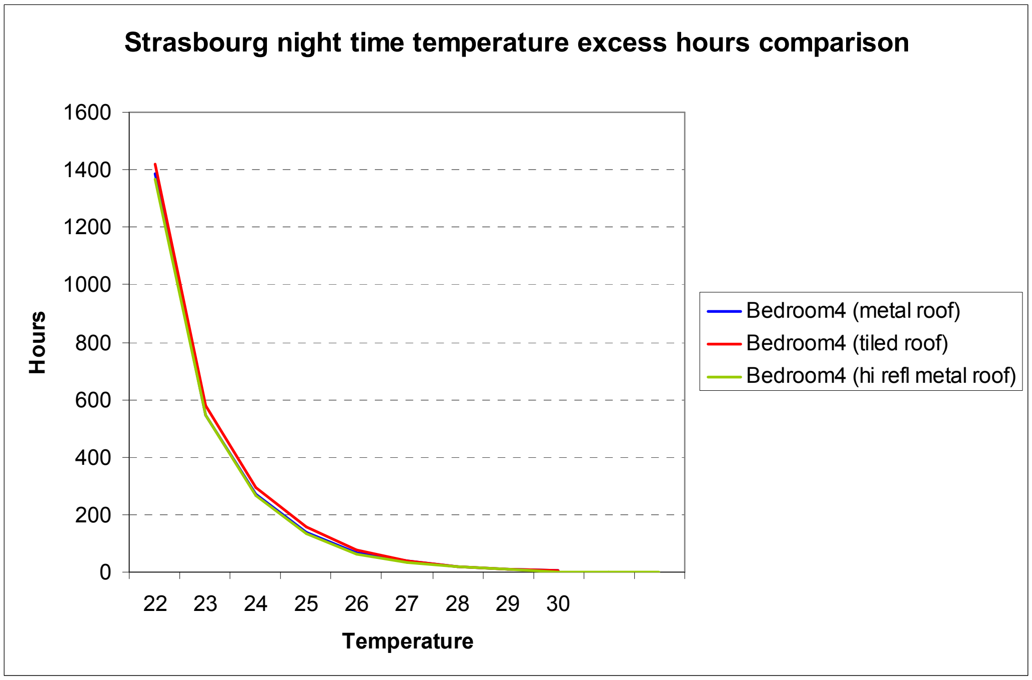


Figure 11. Temperature excess hours (night occupied hours)

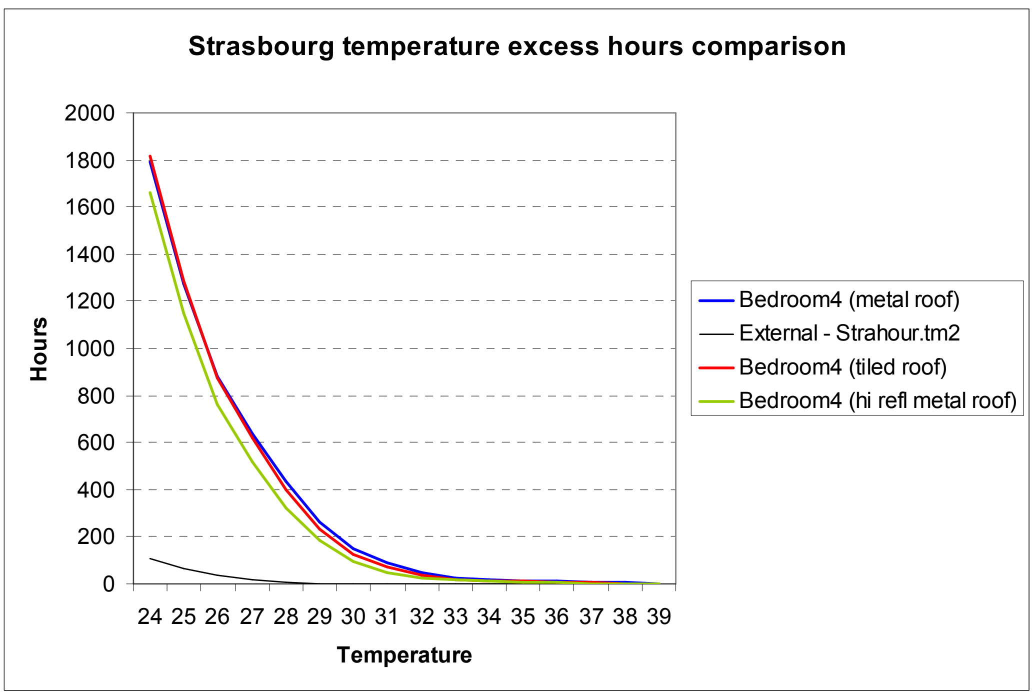


Figure 12. Temperature excess hours (24 hours)

Metal roofs have a very small effect, although the high reflective coated metal roof has a greater effect.

In summary, Strasbourg was selected as a mid-continental climate with relatively high insulation requirements. With this high level of insulation and no major extremes of weather, there was very little effect in any measure of the roofing material on the thermal behaviour of the bedroom. The highly reflective metal roof showed a marginal benefit in reducing hours of overheating, although this was mostly in day time.

3.2. Aix-en-Provence: roof U-value 0.25W/m^{2}K

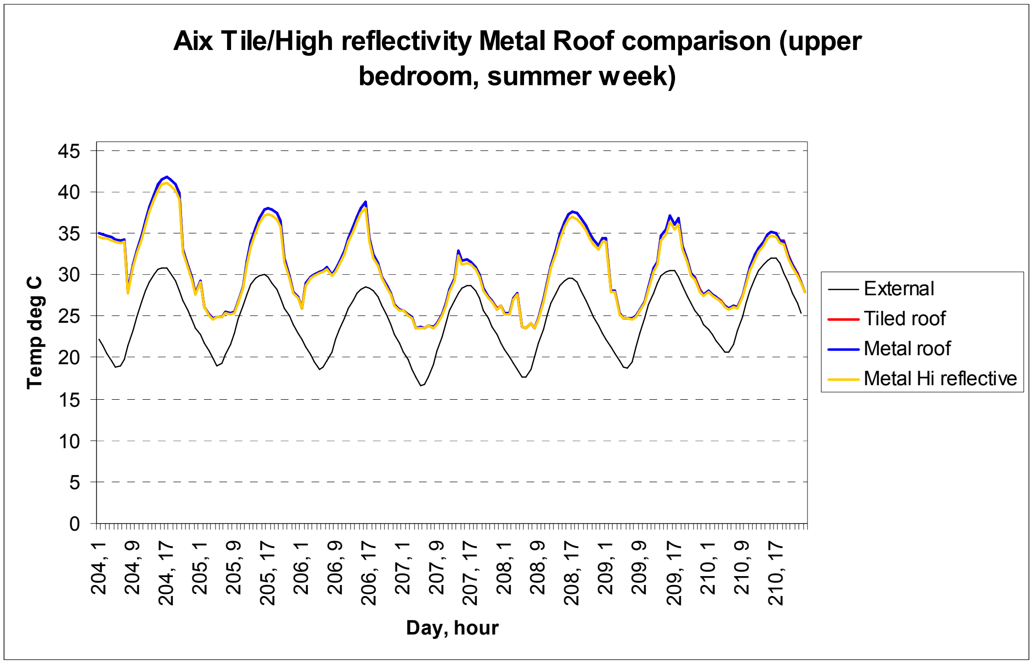


Figure 13.

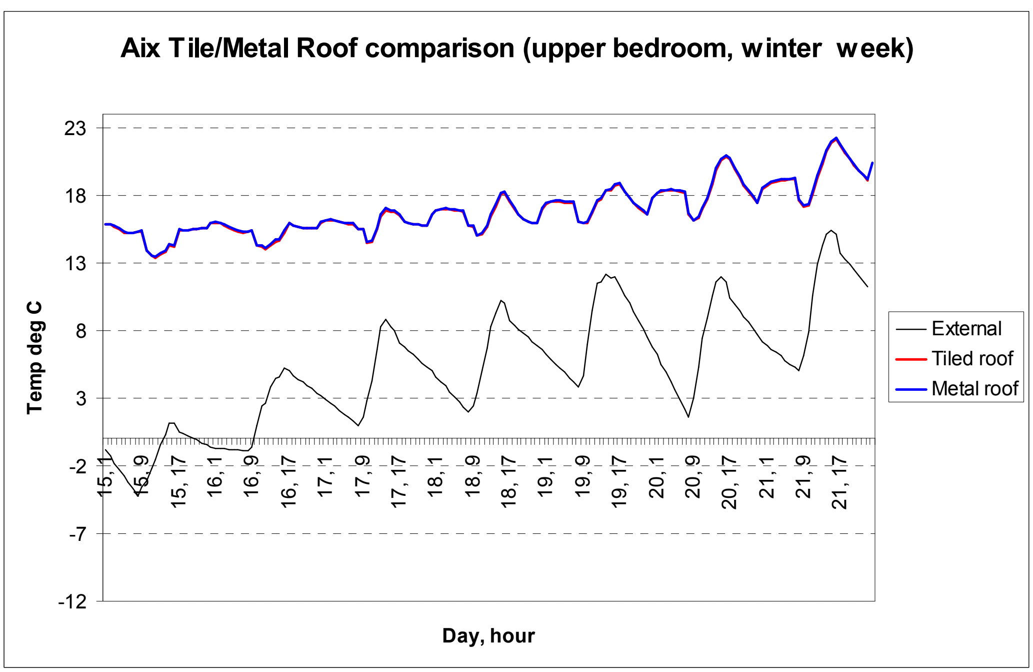


Figure 14.

Little difference is noticeable between the roof types.

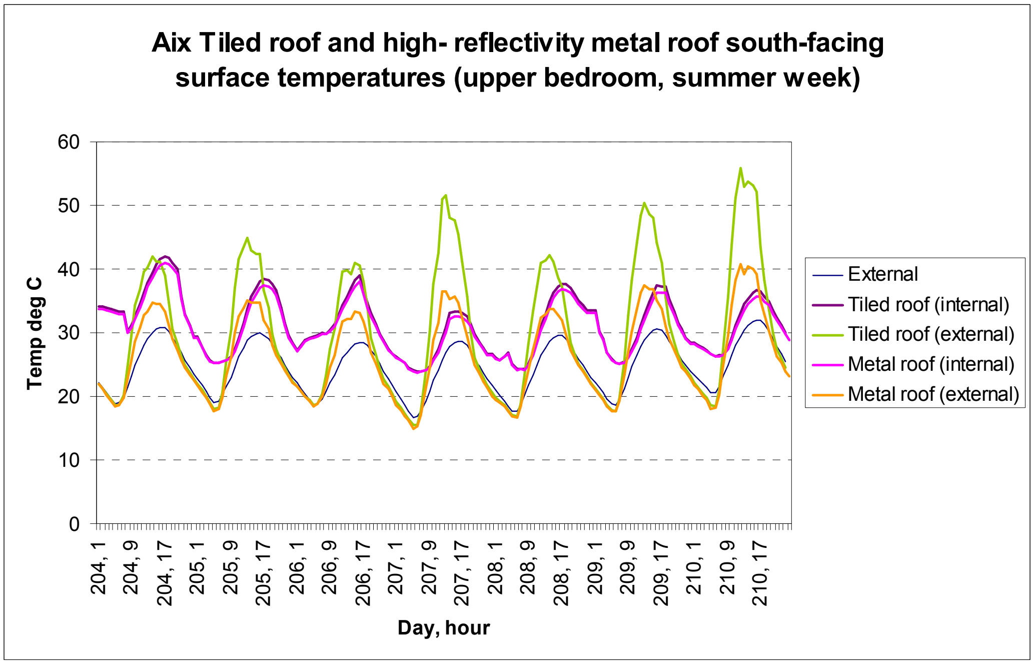


Figure 15.

Value in kWh

Month	Heating (metal)	Heating (tile)	Heating (hi refl)
1	21.99	22.88	25.75
2	7.82	8.31	9.35
3	0.06	0.09	0.16
4	0.00	0.00	0.00
5	0.00	0.00	0.00
6	0.00	0.00	0.00
7	0.00	0.00	0.00
8	0.00	0.00	0.00
9	0.00	0.00	0.00
10	0.00	0.00	0.00
11	3.90	4.13	4.80
12	28.61	29.41	31.44
Total	62.37	64.81	71.49
Peak	0.95	0.97	0.96
Day	359	359	359
Hour	17	17	17

Table 4. Aix heating loads (upper bedroom)

Value in kWh

Month	Metal	Tile	Metal (hi refl)
1	0.05	0.04	0.00
2	0.50	0.48	0.38
3	5.73	5.47	4.33
4	23.46	22.95	20.38
5	14.99	14.94	14.69
6	21.82	21.78	21.36
7	40.99	40.91	40.04
8	25.40	25.41	24.95
9	16.75	16.74	16.42
10	26.88	26.59	24.63
11	3.22	3.09	2.78
12	0.15	0.12	0.05
Total	179.96	178.51	169.99
Peak	2.24	2.24	2.17
Day	204	204	204
Hour	6	6	6

Table 4. Aix cooling loads (upper bedroom)

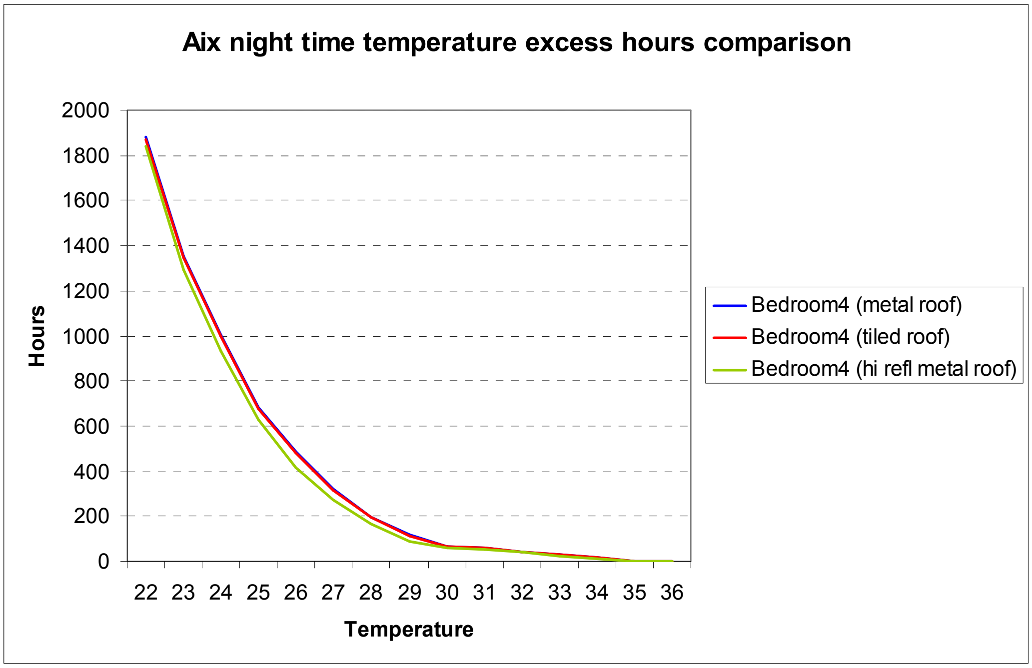


Figure 16.

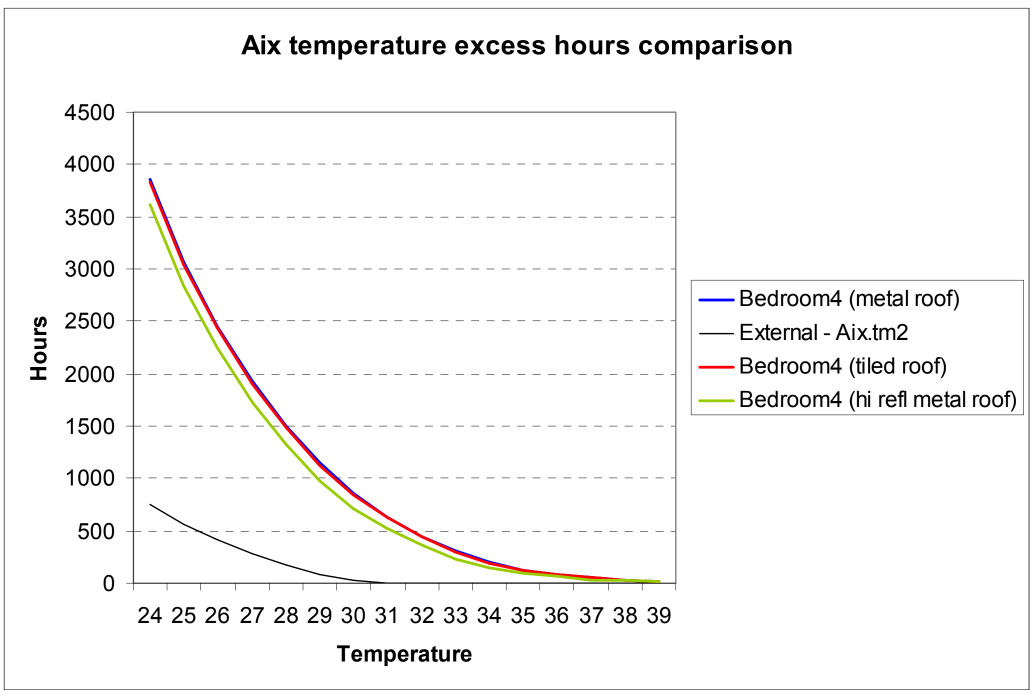


Figure 15.

Aix en Provence was chosen for a simulation due to a lower insulation level and hotter climate than Strasbourg. However, there was again very little difference in thermal behaviour of the bedroom between metal and tile roofs. The effect of the highly-reflective metal roof in reducing overheating was more marked than in Strasbourg and where air conditioning would be used, this would lead to a reduction in energy requirement.

3.3. Naples: roof U-value $0.55 W/m^2K$

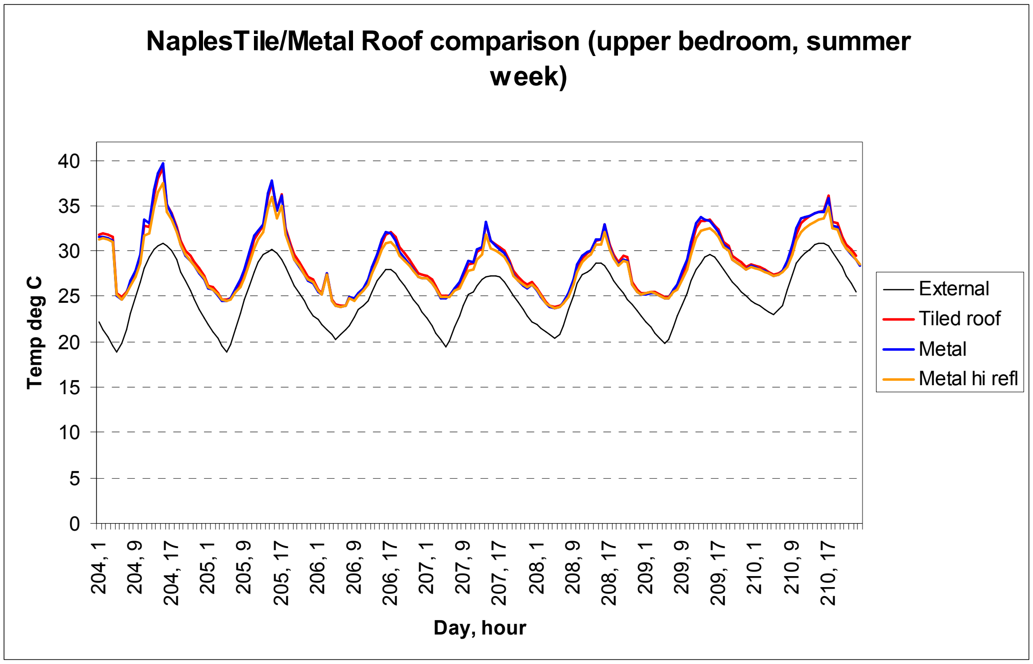


Figure 16.

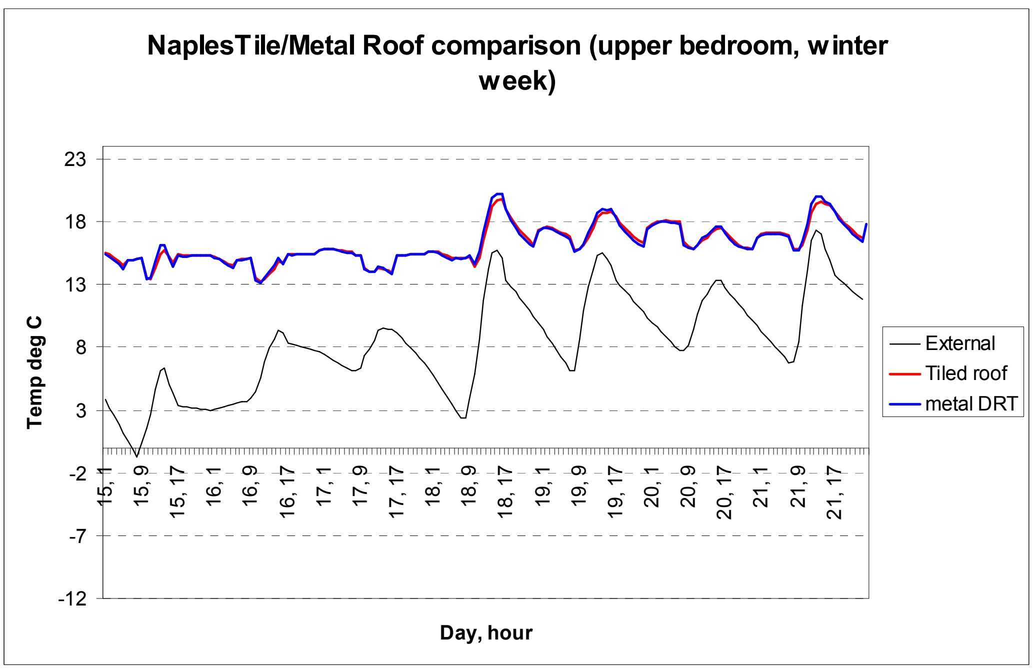


Figure 17.

Little difference is noticeable between the roof types.

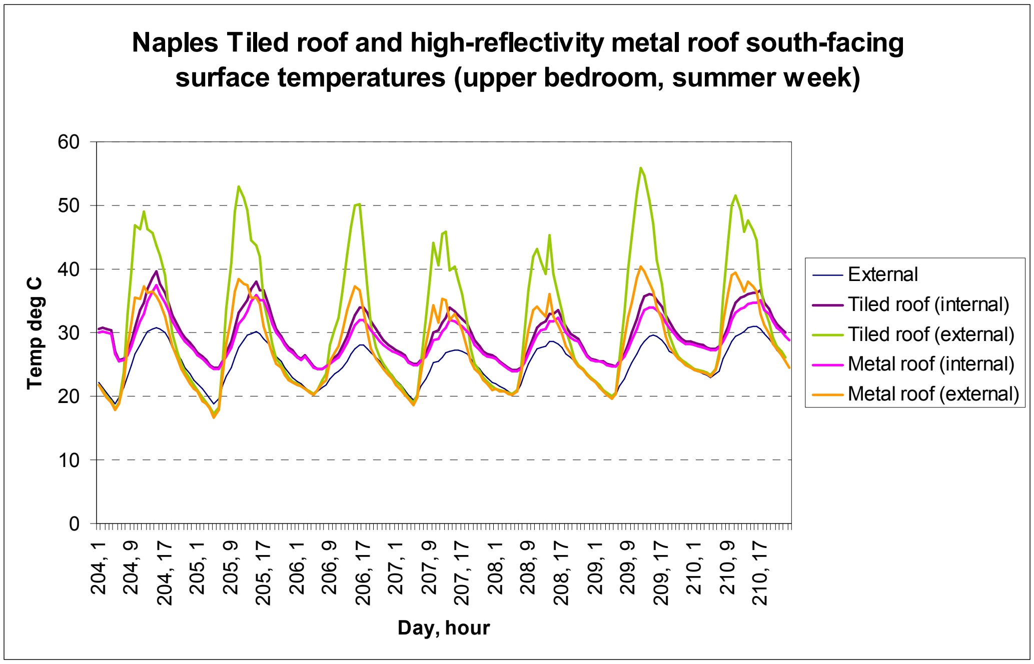


Figure 18.

Value in kWh

Month	Heating (metal)	Heating (tile)	Heating (hi refl metal)
1	38.17	34.05	43.12
2	25.08	21.42	29.71
3	6.83	5.38	9.90
4	0.09	0.08	0.29
5	0.00	0.00	0.00
6	0.00	0.00	0.00
7	0.00	0.00	0.00
8	0.00	0.00	0.00
9	0.00	0.00	0.00
10	0.00	0.00	0.00
11	8.84	7.14	10.50
12	29.62	25.79	34.06
Total	108.63	93.86	127.58
Peak	0.58	0.58	0.60
Day	360	360	46
Hour	8	8	8

Table 6. Naples heating loads (upper bedroom)

Value in kWh			
Month	**Metal**	**Tile**	**Metal (hi refl)**
1	0.07	0.09	0.01
2	0.05	0.19	0.00
3	1.13	2.20	0.75
4	9.56	13.07	7.80
5	23.43	24.66	22.37
6	40.50	41.02	38.90
7	57.35	59.90	57.37
8	55.68	59.44	57.01
9	37.82	40.66	39.03
10	29.04	34.59	28.93
11	3.40	4.44	3.12
12	0.45	0.67	0.39
Total	258.47	280.92	255.67
Peak	1.77	1.96	1.90
Day	232	232	232
Hour	6	6	6

Table 7. Naples cooling loads (upper bedroom)

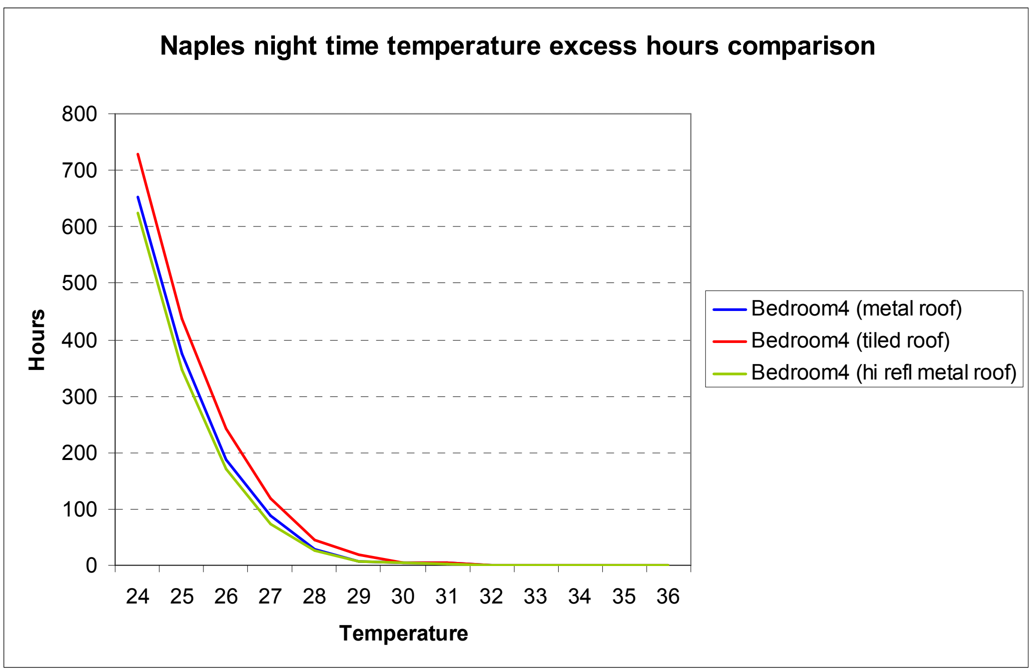


Figure 19.

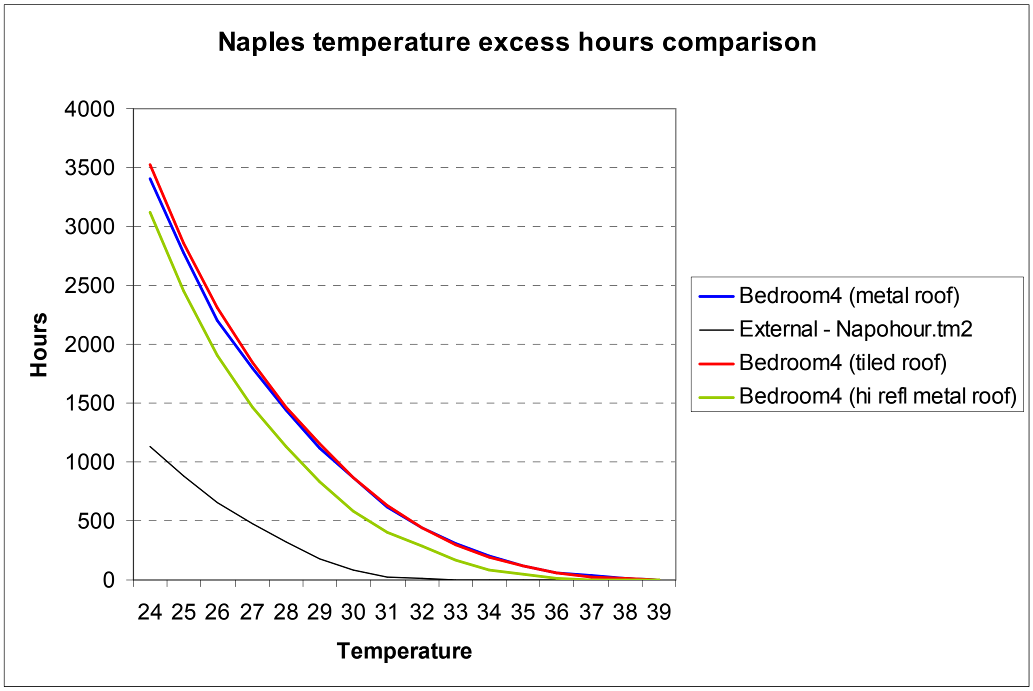


Figure 20.

Naples represents a hotter climate than either of the two French examples, with a much lower insulation requirement. In this case, a small difference could be seen in internal temperature between the three roof types modelled. The thermal capacity of the tile roof did reduce the peak mid-day temperature marginally, but this was soon negated as it failed to cool down in the afternoon and retained heat into the evening. The reflective metal roof was far more effective at reducing peak internal temperature, retaining this benefit throughout the day. Whilst the reflective metal roof showed a significant benefit in reducing overheating throughout the day, when assessing night-time use (for the bedroom) the standard metal roof was almost as effective and gave a significant benefit over the tile roof. This is reflected in reduced cooling loads for the metal roofs.

3.4. Athens: roof U-value 0.5 W/m^{2}K

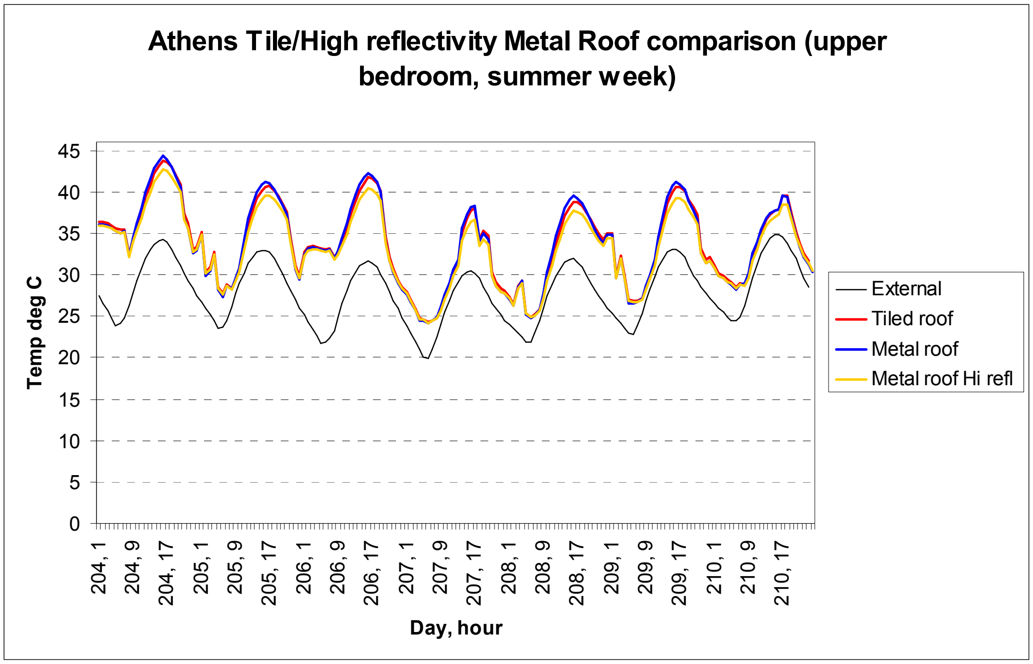


Figure 21.

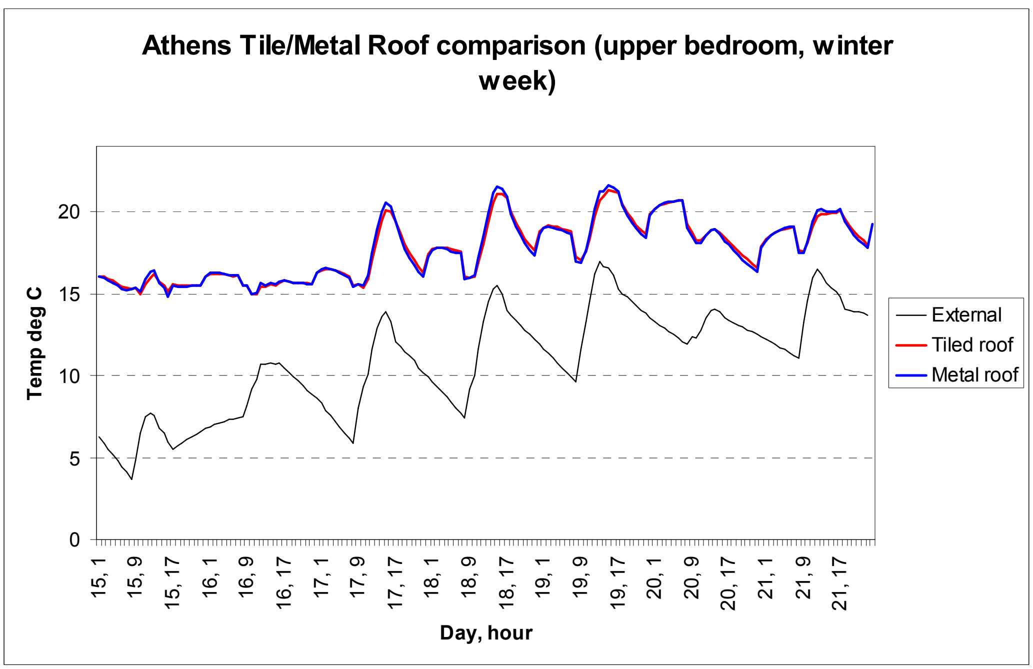


Figure 22.

Little difference is noticeable between the roof types.

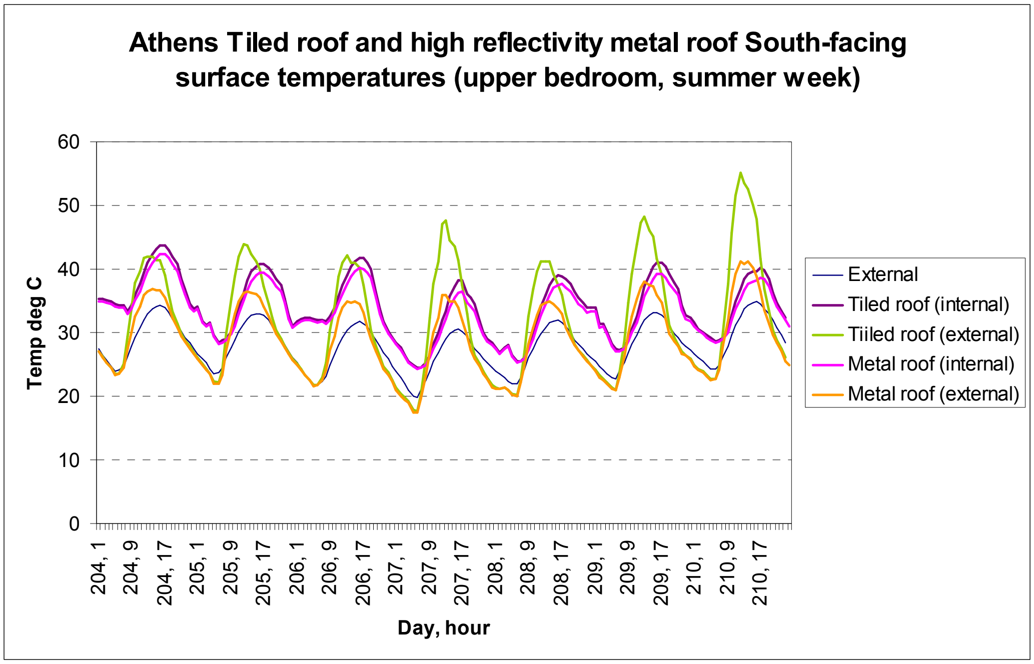


Figure 23.

Value in kWh			
Month	Heating (metal)	Heating (tile)	Heating (hi refl metal)
1	11.70	10.20	13.38
2	9.56	8.09	10.69
3	3.36	2.50	4.26
4	0.00	0.00	0.00
5	0.00	0.00	0.00
6	0.00	0.00	0.00
7	0.00	0.00	0.00
8	0.00	0.00	0.00
9	0.00	0.00	0.00
10	0.00	0.00	0.00
11	0.08	0.01	0.11
12	7.79	6.74	8.72
Total	32.49	27.54	37.16
Peak	0.49	0.49	0.51
Day	13	13	13
Hour	8	8	8

Table 8. Athens heating loads (upper bedroom)

Value in kWh			
Month	**Metal**	**Tile**	**Metal (hi refl)**
1	2.24	2.67	1.96
2	2.33	3.02	2.00
3	7.21	9.08	6.90
4	26.16	31.00	25.72
5	37.36	39.97	38.30
6	58.66	63.29	60.96
7	89.81	98.63	95.78
8	89.94	99.48	96.56
9	57.54	63.15	61.16
10	48.67	54.71	50.76
11	17.20	19.42	17.26
12	6.67	7.54	6.38
Total	443.77	491.94	463.73
Peak	2.86	3.19	3.13
Day	203	203	203
Hour	6	6	6

Table 9. Athens cooling loads (upper bedroom)

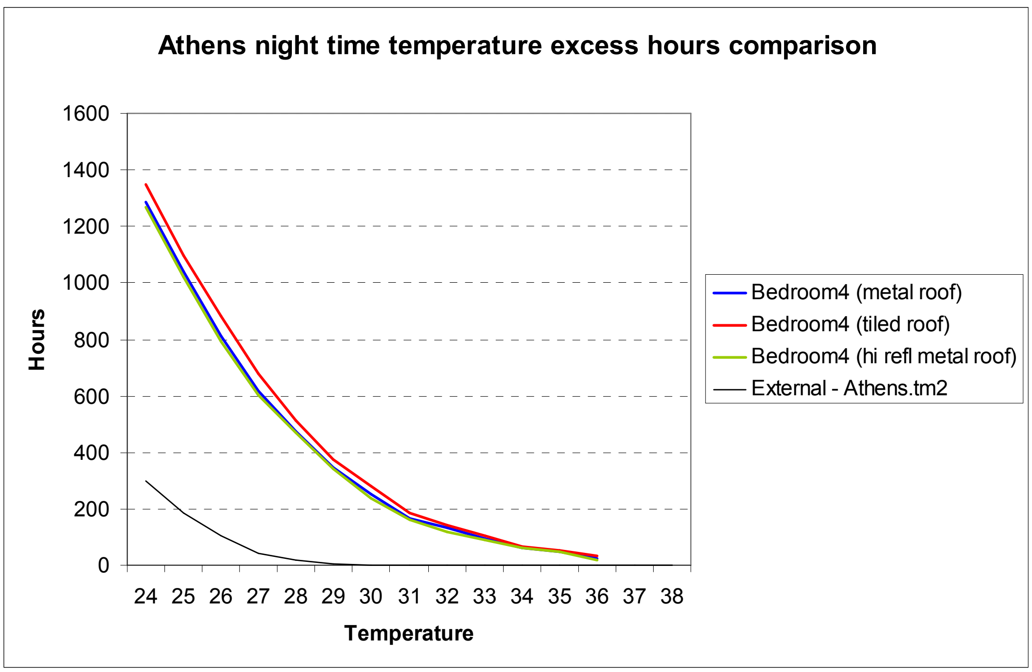


Figure 24.

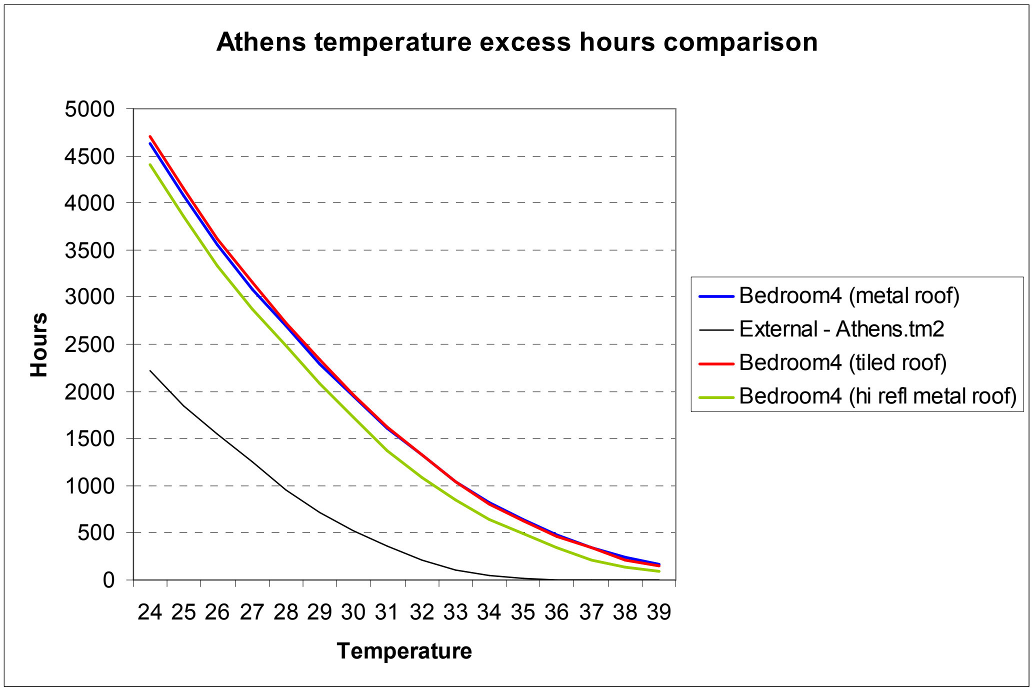


Figure 25.

Athens represented the hottest climate modelled and as expected, the effect of the roof material was greatest. The trends are similar to Naples with both metal roofs giving benefits during afternoon, evening and night compared to the tile roof, while the reflective metal roof also consistently reduces day-time overheating too. This is again reflected in a reduction in demand for cooling and so a lower energy usage of the houses with metal roofs.

3.5. Urban Heat Island considerations

The principal causes of the urban heat island (UHI) are the storage by day of solar energy in the urban fabric and release of this energy into the atmosphere at night, and the fact that the process of urbanisation alters the balance between the energy from the sun used for raising the air temperature (heating process) and that used for evaporation (cooling process) because vegetated surfaces are replaced by impervious engineered ones. Given this, strategies for tackling the root causes of the UHI need to focus on controlling the absorption and release/escape of heat from the urban fabric and tipping the balance between the apportionment of available natural energy between heating and cooling of the urban atmosphere.

***Cool roofs**: Many of the roofs across London are dark in colour and probably reach temperatures in excess of 50-60 degrees C on hot sunny days. Consequently they will store and release a considerable amount of energy back into the atmosphere. High roof temperatures will accelerate the deterioration of roof materials and in buildings with poor roof insulation contribute to increased demand for cooling energy and a decrease in indoor thermal comfort on upper floors. In contrast cool roofs built from materials with high solar reflectance or albedo and high thermal emittance may reach temperatures considerably lower than their low reflectance counterparts. This is because they absorb and store less solar energy during the day and thus are not major emitters of heat into the urban atmosphere at night. Apart from their reduced contribution to the development of the nocturnal heat island, cool roofs have obvious benefits for the lifetime of roofs as excessive contraction and expansion is avoided through a damped daily temperature range and absorption of ultraviolet radiation is reduced. Also there will be gains in terms of indoor thermal comfort through the reduced transfer of heat through roofs to the upper floors of buildings and reduced demand for active cooling systems. To ensure the effectiveness of cool roofs as a climate management strategy their reflectivity must be maintained as this declines with roof age and roofs need to be kept clean, as dirt and pollution lower reflectivity.*

Source: London's Urban Heat Island: A summary for decision-makers, GLA, 2006

As the clipping above shows, the urban heat island effect is a problem which faces cities across the world, not just in hot regions. In the current study, roof surface temperatures were also recorded over the summer period (May-September) for the three different roof types. As an example, for the Athens climate:

Tile maximum temperature:	67.6°C
Metal maximum temperature:	64.6°C
Reflective metal maximum temperature:	46.8°C
Tile average daytime temperature	41.9°C
Metal average daytime temperature	40.1°C
Reflective metal average daytime temperature	33.2°C

If a solar reflective coating is used (r=0.7), the maximum surface temperature of the roof is reduced by over 20°C in this case.

Similarly, the average summer daytime surface temperature of the roof (1000hr – 1600hr) is reduced by nearly 9°C.

There is less heat stored within the roof fabric when a metal roof is used instead of tile, helping to reduce temperatures overnight. Besides the actual temperature achieved, stored heat in thermally massive elements such as tile roofs is a major contributor to the urban heat island effect.

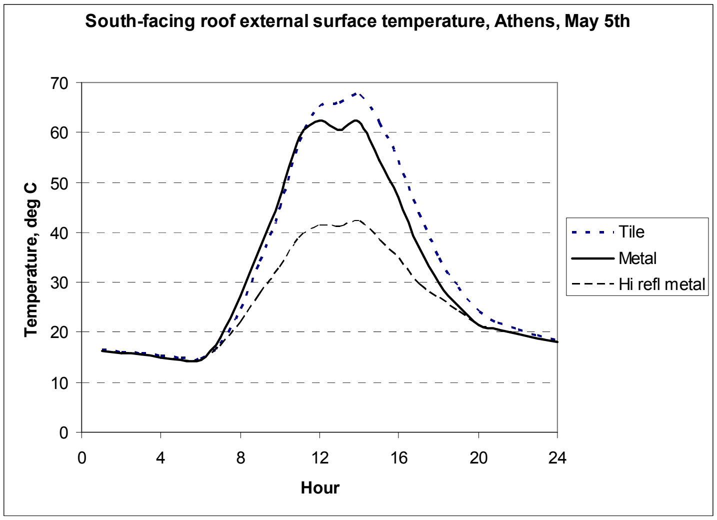


Figure 26.

4. Conclusions

Dynamic thermal modelling has shown that the choice of a metal or tile roof makes little difference to the thermal performance of housing across much of Europe, partly due to the level of thermal insulation used. A small difference is apparent in hotter climates where the thermal inertia of tiles leads to greater overheating, particularly in bedrooms. The ability to incorporate a heat-reflective coating in the metal roof made the difference even more apparent.. Where a metal roof is used, cooling loads can be reduced if the house is air-conditioned, or hours overheating are decreased if no cooling is used.

Metal roofs can have a beneficial effect upon urban heat islands, particularly where solar reflective coatings are used, reducing both peak and average summertime surface temperatures during the day. All metal roof types will reduce heat stored in the building fabric which is a major contributor to urban heat islands.