TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

Report on the

Research Project

Residential Buildings, Using Comparative Measurements"

“Case Study of the Differences between Infrared Heating and Gas Heating in Old

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Summary

In the 2008/2009 heating season, a case study involving comparative measurements to ascertain differences in energy consumption between infrared heating and gas heating was carried out in order to provide an evaluation of the fundamental utility and capability of infrared heating in a residential area against the background of the structural change in the area of energy supply.

The presented research was able to prove that infrared heating is a realistic alternative to standard heating systems.

If infrared heating is used correctly, advantages in terms of energy consumption can be seen, as well as in the areas of costs and the CO_2 balance.

Preface

General overview, stating the aim of the project

In the 2008/2009 heating season, comparative measurements to ascertain differences between heating via infrared radiation (infrared heating in short) and heating with gas were carried out.
The aim was to determine the energy consumption and costs of energy for a specific example, and using this example, to attempt a generalized evaluation of the energy balance from the ecological point of view as well as of the total costs of both heating systems.

Motivation and background

At present, the energy market is distinguished by significantly growing costs for the carriers of fossil energies. Also, the temporary impairment of this development, which is a result of the worldwide financial crisis, has to be understood as being transient and as a short 'time-out period', and this can be already seen today.
Owners and landlords of old buildings with significantly high energy consumption for heating are particularly suffering from this price increase. It is true that there are various state incentives for renovation work, but the needed financial means are absent in many cases. This is the case despite wide-ranging supportive measures from the state.
As a possible solution, electrically powered infrared heaters are being offered on the market. The aim of this project is to evaluate the fundamental utility, economy and ecological sense of this solution in the case of one example.

Acknowledgements

The manager of the project wishes to convey his heartfelt thanks to the Dietz-Groß family for their approval of all needed installations, for the opportunity to carry out measurements under everyday conditions and for all their support during the project.

Heartfelt thanks also to the firm Knebel, which was a partner that abstained from creating any bureaucratic obstacles and provided an infrared radiator and measuring devices.

Important notice

Due to the great general interest in this topic, this report is conceived in such a way that even a non-specialist who is interested in the given issues can understand it. Therefore, it contains an easy-to-understand description of the physical background to this topic, as well as of heating engineering and the fundamentals of air-conditioning technology. For more detailed information regarding the given issues, internet pages which are extensive and fairly easy to understand are also listed alongside specialized articles.

This research report will be issued in several versions, depending on feedback from readers and the subsequent extended evaluation of the measurement results. Questions, stimuli, criticism and suggestions for the improvement of future versions are highly welcome!

The most current version can always be found at

http://www-user.rh rk.uni-kl.de/~kosack/menu1/1 .shtm

Contents

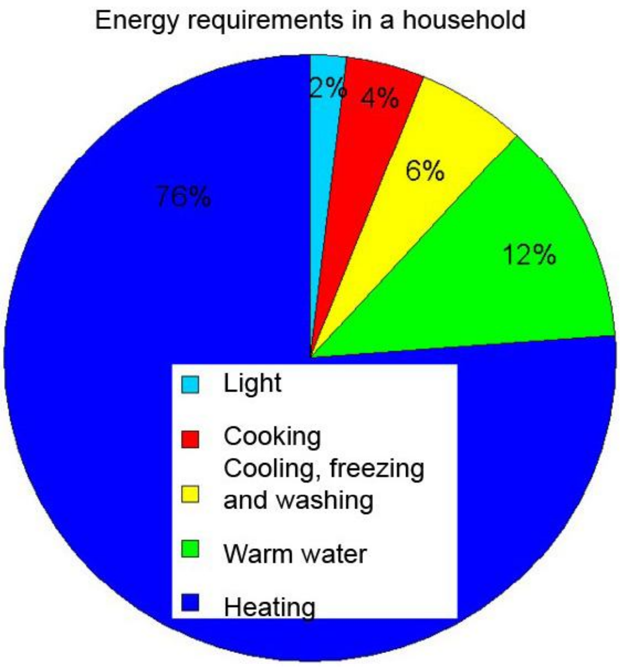
1 Introduction

1.1 Basic explanation of the definition of the goal of heating

Heating is generally used to keep the internal temperature of buildings within a range which is bearable for people or which even enables their survival, despite falling outdoor temperatures. It is essential in areas where outside temperatures can drop dramatically under 20 °C.

For this purpose, the term ‘heating season’ was defined. The term ‘heating season’ describes a period in which heating is put into operation in order to maintain the indoor temperature at the guideline value of 20 °C. A relative value in Germany is the mean outdoor temperature, 15°C, which is known as the ‘heating limit’.

There are no legal regulations for the heating season because the need for and dimensioning of the heating system depends on climatic conditions, geographical situation and height above sea level as well as on other factors such as the standard for the insulation of the building, and all of these elements are different in every location. It is even possible, in an extreme case, to insulate a building so well that no heating system is needed even in areas below freezing point and the pure heat generated during usage of the building is sufficient.
Common insulation standards, particularly as far as durability is concerned, range much below this limit. On average, heating forms 76% of the energy requirement of a household at present (See pic.1.1) Therefore, a heating system which fulfils its heating goals with maximum stability, efficiency and in a cost-friendly way is essential.



Pic. 1.1: Energy requirements in a household

1.2 Motivation for the presented research

The motivation was the question as to whether infrared heating provides a realistic solution for heating problems, and the sub-questions were:
Is it suitable at all for use as heating in residential buildings?
Are the costs competitive with regards to other heating systems?
Is the ecological balance competitive with regards to other heating systems?
Is it useable in practice?
Is it available without limitations, i.e. what would happen if everybody started using it?

The previous project by the working team, Ecological Housing Construction in the Years 1994 – 1996 had already researched these questions. It examined the suitability of infrared heaters of the type that has a heating wire wound into a helix (bathroom and church radiators) in a low-energy house. As a result of apparent discrepancies between oil/gas and electrical energy prices at that time, the research was terminated prematurely. Apart from that, the structural form of the radiators used at that time as the sole source of heating for permanent use proved to be unsuitable.

With the changes in energy prices and the ability to succeed in promoting the plane radiator structural form on the market, radiators which work almost without wearing out and are suitable for permanent operation, this topic was revisited.

First, market research was carried out on the internet in order to select suitable plane radiators.
The main selection criterion was the physical suitability of infrared radiators (see also below):
surface temperatures in the area of approx 60°C to 120°C (more than 50% from pure radiation) and no storage mass (fast reaction when switched on and off).

Subsequently, contact was made with the producer of the selected product and cooperation in the research was arranged.

It is necessary to point out explicitly at this point that this isn't a work of comparative research evaluating various producers or products but is rather a study concerned with the overall suitability of infrared radiators, particularly those of the plane type, for the heating of rooms in residential areas.

1.3 Documentation and background information needed for understanding this project, and its evaluation

1.3.1 Energy management documentation and sustainability

The term energy management describes the whole infrastructure that is necessary for the provision of energy supply.

It encompasses the accessibility of energy resources, obtaining of energy, storing of energy, energy transport, energy transformation and trading in energy.

Form the point of view of cosmic space, three principal available sources of energy exist as the primary base of any energy economy and all other energy carriers are created by their transformation: solar radiation, gravity and the heat generated by the planets themselves.
Background radiation as a theoretical fourth source is not useable as far as energy management is concerned. Background radiation is any kind of electromagnetic radiation which is created by stars, pulsars, quasars etc. in the depths of the universe and is sent to our solar system from the outside.

Solar radiation is created by nuclear fusion in the Sun. It facilitates life on our planet Earth and is far and away the greatest useable source of energy in the solar system. Due to this, experiments are being carried out in nuclear physics with the aim of making this source of energy useable in the form of technically possible nuclear fusion on the Earth. However, the physical and technical problems surrounding this haven't yet been solved, to a large degree, and so this source of energy won't be available in the near future and is, one could say, a very unsure prospect.

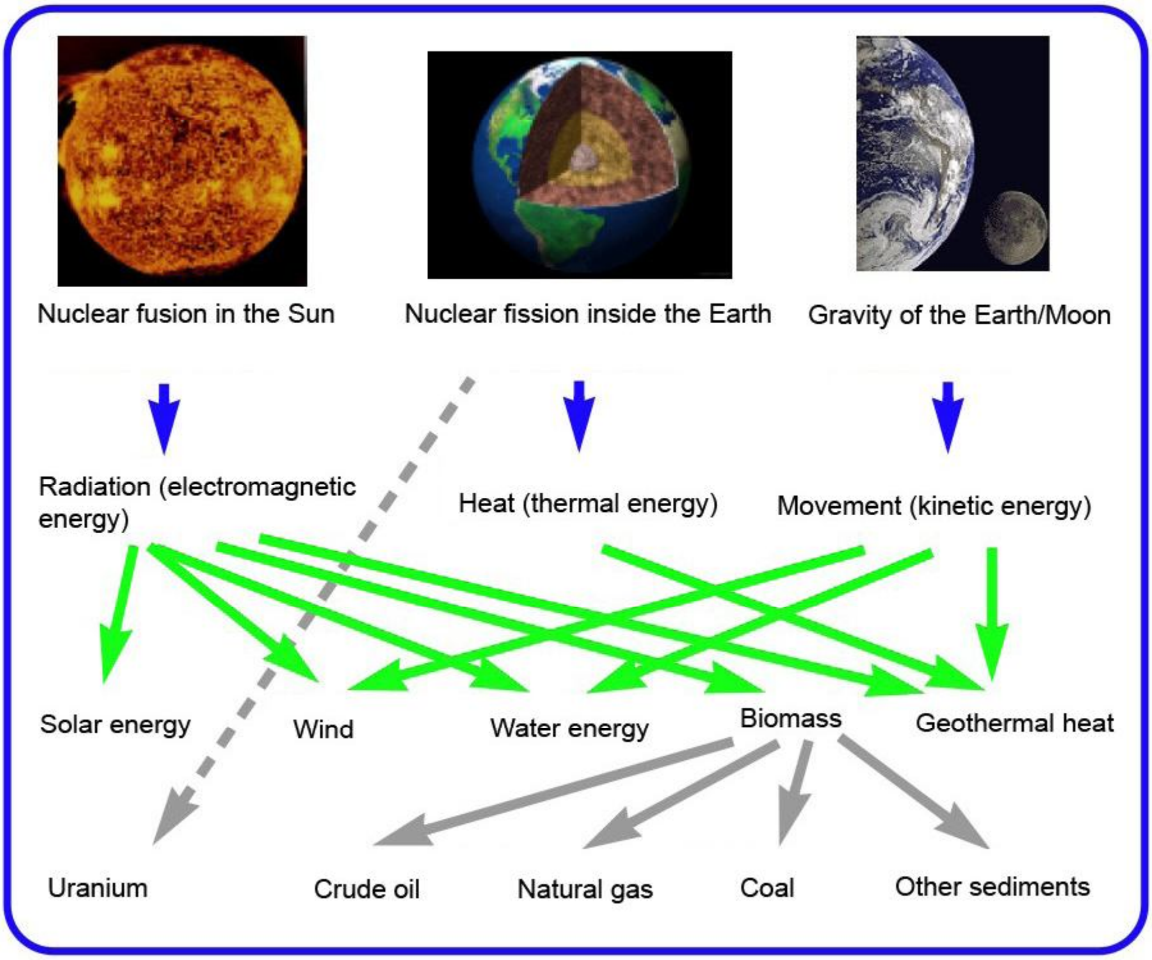
Gravity, which is caused by the mass of heavenly bodies, can be used because the Moon orbits the Earth. Thus e.g. low and high tides are created bringing the possibility of gaining energy from tidal power stations. The Earth's own warmth is created mainly by fission within the Earth's core. This heat can be used e.g. geothermically.

Displayed in **pic. 1.2** are three useable primary sources of energy and renewable and fossil forms of energy, or energy carriers.

1. Through nuclear fusion in the Sun, electromagnetic energy in the form of radiation is created which can be used directly and indirectly.
Direct usage of radiation takes place in the case of solar energy by the transformation of sunlight into electrical energy or heat.
Indirect use of radiation in the case of wind, water power and geothermal heat takes place by absorption, i.e. the absorption and transformation of radiation into heat. Wind appears as a result of the heating of air and this is transformed into electrical energy in wind power plants. Heated water evaporates and forms clouds from which rain falls. Thus, streams and rives are created on which hydro power plants can be built. In the case of geothermal heat, the top layers of soil are heated as a result of solar radiation. This accumulated heat is used via heat pumps and ground heat exchangers.
The indirect usage of radiation in biomass takes place during photosynthesis in plants. The most frequently used and also created energy carrier is wood.

2. As a result of nuclear fission inside the Earth, heat is created which can be used in various ways with the help of geothermal energy devices.

3. As a result of gravitational forces between the Earth and the Moon, kinetic energy is created which causes the movement of the atmosphere and the world's seas.
The moving atmosphere contributes to wind energy. From the movement of sea waters, such as low and high tides, electrical energy is gained in tidal power stations.



Pic. 1.2: Usable energy spectrum

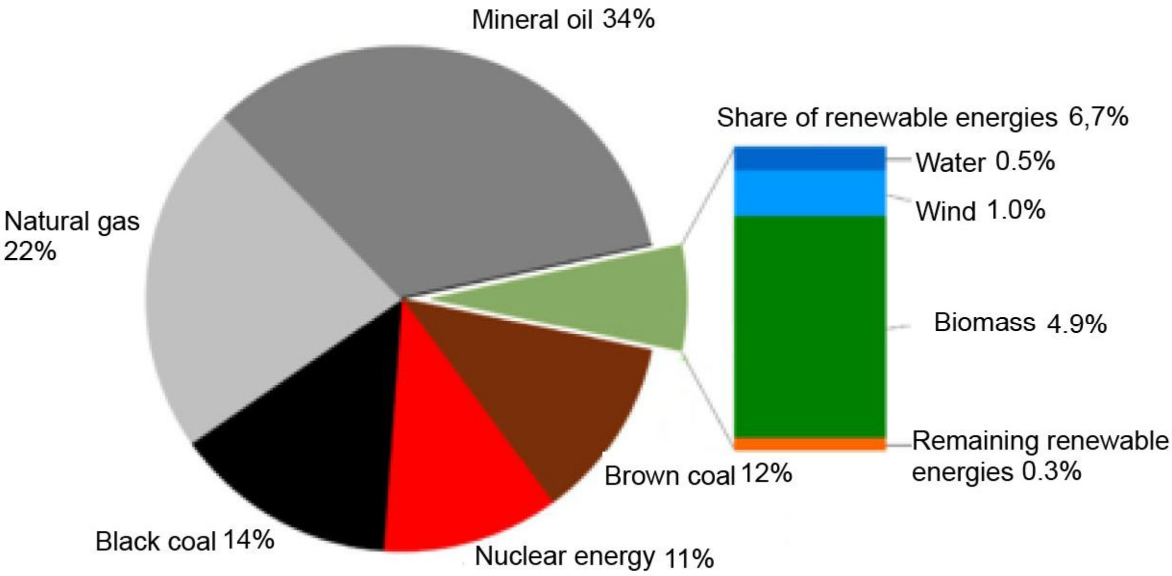
The fossil energy carriers coal, crude oil, natural gas and other sediments were created from biomass over millions of years due to the work of geological processes. These are the energy sources which are used the most today.

The element uranium is a special case - it is used for the creation of electrical energy in nuclear power stations. It is one of the radioactive elements which provide the inner heat of the Earth and it is obtained from mines. In nuclear power stations, radioactive energy is transformed into heat and from it, electrical energy is manufactured. In actual fact, this is a technological detour. The direct way would be to obtain energy from nuclear energy, as in the case of other radioactive elements, with the use of geothermal heat directly from the inside of the Earth.

The main carriers in German energy management are the crude oil industry, coal mining industry, electrical energy suppliers and gas and distance heating businesses.

As can be seen in pic. **1.3**, most electrical energy is still supplied by fossil energy carriers.

Since the 1990s, private households in Germany have a share in this due to the legal support of energy management based on renewable energies (law on electrical energy supply, law on renewable energies).



Pic. 1.3: Primary energy consumption in Germany

The term *Sustainability* originally comes from forest management. There, it describes the method of forest management where only so much wood is taken as can manage to grow back, and thus the forest is never cut down completely and it can regenerate to its full extent.
Generally speaking, “sustainability” means a way of using a system that preserves its relevant structures and properties and allows its existence to regenerate in a natural way. In energy management, the conditions of permanence are only fulfilled in the case of renewable energy sources because they provide a permanent – in a figurative sense “re-growing” – stream of energy which from the human perspective is endless.
As a result of the limits of fossil energy carriers and the growing amount of negative side effects of their use, such as global warning, pollution of the environment, the growing cost of energy as a reaction to their scarcity and their social consequences, it is essential to change our orientation towards renewable energies as swiftly as possible. This conclusion was already laid out within the international contract of Agenda 21 at the “United Nations Conference on Environment and Development” (UNCED) in Rio de Janeiro in 1992, which was signed by almost every country in the world.

As the amount of energy which is needed for the purpose of heating makes up about three quarters of the total energy requirements of the average household, the most urgent task is a fast transition to the use of renewable energy carriers.

1.3.2 Basics of heating and technology

Thermal energy (heat energy)

Thermal energy (also called heat energy or heat) is energy which is stored in the subordinate movement of the atoms or molecules of a substance. It is a state quantity and is measured in measuring units called joules.

Thermal energy and temperature depend on each other according to the formula

$E_{th} = m * c * T$

where E_{th} is thermal energy, T is absolute temperature, m is weight and c is specific heat capacity. The specific heat capacity is itself dependent on the temperature, i.e. its relationship is not proportional. There are so called phase transitions, as in the case of melting ice, for which one part of the energy input is used up for the melting itself without any increase in temperature.

When two systems have different temperatures these temperatures adapt themselves via heat transfer from the warmer system to the cooler one until both of them have the same temperature. This is then called thermal equilibrium. Heat transfer can take place via heat conduction, convection (flow) or radiation of heat.

Heat conduction

During heat conduction (which is also called heat diffusion), heat is gradually transferred further as a result of temperature differences in a solid substance or still liquid by the interaction of inner molecular forces. This also takes place between several bodies made of solid substances or liquids which touch each other and are at rest in relation to each other. According to the law of conservation of energy, no heat loss takes place during this process. During the conduction of heat, thermal energy, but not particles, is carried from one place to another.

In thermal technology, effects resulting from heat conduction are usually negligible. They only play a role in the case of losses, e.g. due to the poor insulation of burners and pipelines.

(Recknagel, Sprenger, Schramek: Handbook for Heating and Air-conditioning Technology, Oldenbourg Wissensch.Vlg; issue 68 (1997/98), p. 135 ff)

Convection

Convection is a means of heat transfer which is based on the transfer of particles which conduct thermal energy. In heat technology, it is convection without exchange of matter, i.e. heat transfer takes place from a solid body to a liquid (e.g. water or air) which then takes over the heat transfer. On the thermal border layer between the solid object and the liquid, thermal conduction first takes place between the surface of the body and the particles of liquid which are located immediately on the surface of the object. No thermal balance occurs because, according to the drop in temperatures, the heated or cooled particles are either taken away or are replaced by new ones to which the original temperature drop is related.

During warm-water heating, which is the most common form of heating in apartment buildings, water is the medium for heat transfer by convection in a closed pipeline circuit between the burner and the inner surface of the heating body. Thermal energy passes from the inner to the outer part of the heating body by convection. On the outer part of the heating body, the medium for heat transfer is the air. So-called free convection takes place here, i.e. the air expands due to heating and it moves upwards, while cooler air from below flows above the ground. Instead of the most frequently used heating bodies – radiators – surface heating bodies can be used: water-heated floor, wall or ceiling surfaces or other structures. Convection takes place everywhere in principle.

The thermal output transferred by convection from the heating body into the air is in proportion with the temperature difference between the heating body and the air, and it is governed by the formula:

$P_{HL} = w * A * (T_H - T_L)$, where w is the heat transfer coefficient in (W/m^2K), A is the surface of the heating body, T_H is the temperature of the heating body and T_L is the air temperature.

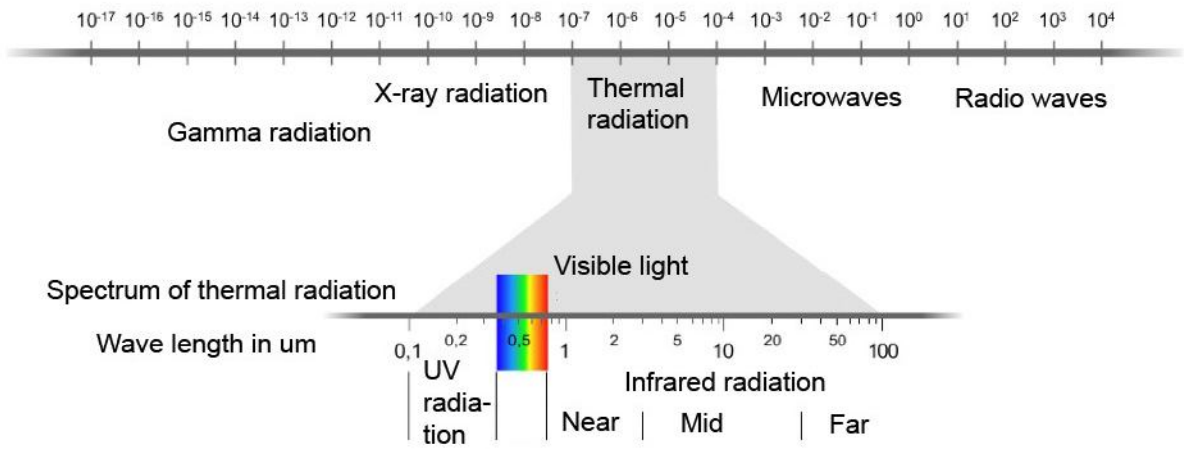
Convection for a given heating body is thus dependent mainly on the temperature difference between the heating body and the surrounding air in the room.
(Recknagel, Sprenger, Schramek: Handbook on Heating and Air-conditioning Technology, Oldenbourg Wissensch.Vlg; edition 68 (1997/98), p. 146 ff)

(Dillmann, Andreas (2005): Karl Wieghardt: Theoretische Strömungslehre (Theory of Fluid Mechanics), Universitätsverlag Göttingen)

(H. Oertel (publisher): Prandtl - Führer durch die Strömungslehre. Grundlagen und Phänomene (Prandtl - Guidebook to Fluid Mechanics. Fundamentals and Phenomena), Vieweg 2002 (11th edition)

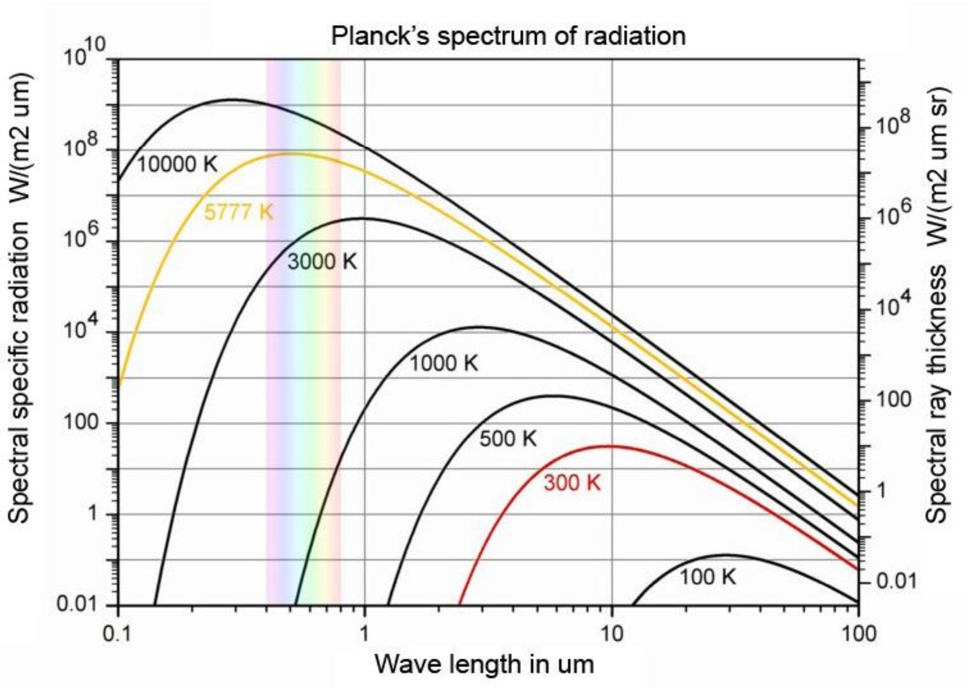
Thermal and infrared radiation

The term thermal radiation describes that part of the spectrum of electromagnetic radiation which every object radiates in relation to its temperature when this temperature differs from absolute zero on the Kelvin temperature scale (0 K). As a form of heat transfer, it isn't dependent on mass, and in contrast with heat conduction and convection, it also appears in a vacuum. The best known form of thermal radiation is solar radiation, which can be divided into the areas of UV radiation, visible light and infrared radiation (see **pic. 1.4**)



Pic. 1.4: Thermal radiation in the electromagnetic spectrum

Spectral division of the intensity of radiation (Planck's spectrum of radiation) is dependent on the surface temperature of the radiant object. The higher the temperature of the surface of the object, the higher the maximum intensity is and the further this maximum moves toward the shorter wavelengths.



Pic. 1.5: **Radiation spectrum of an ideal black body**

Pic. 1.5 shows idealized spectrums for a so called "black body". As an example, the radiation of the human body (300 Kelvin) and the Sun (5 777 Kelvin) can be mentioned. The idealization of a black body means that the depicted spectrum will completely de-radiate. In reality, only so called "grey bodies" exist in which the radiation is assessed with the coefficient *t* (0<e<1). The value *t*, however, approximates the value of 1 for the majority of surfaces in buildings. Therefore, there usually isn't any remarkable difference between black and grey bodies in practice.

It is important not to mistake the radiation coefficient *t* (also called the radiation coefficient) with the efficiency of radiation of an infrared radiator. It is a frequent mistake when stating technical information about the products offered on the market. The radiation coefficient states the output of radiation of the infrared radiator in proportion to the output of an ideal black body; the efficiency of radiation is the ratio of the discharged output of radiation in relation to the supplied electrical output.

(see also: Fröse, H.-D.: Electric Heating Systems, Pflaum Verlag 1995, 23ff)

According to the Stefan-Boltzmann Law the total intensity of radiation of a body is:
$M = \sigma * T^4$ (Stefan-Boltzmann Law), where $\sigma = 5.67 * 10^{-8}$ W/(m^2K^4) (Stefan-Boltzmann constant) and T = the absolute temperature of the surface of a body.

The total intensity hence increases strongly with the fourth power of the temperature. For every square metre of its surface, the Sun radiates approximately 400 times the output of radiation in comparison with a human body, even though the temperature is only somewhat more than 19-fold.

Idealization is also used first with the Stefan-Boltzmann Law. This is applied as if the body was alone in the universe. In reality, many objects influence one another as a result of mutual radiation exchange. The energy of radiation given off from the surface of one object is partially absorbed and partially reflected from the surface of another object. The absorbed amount of energy contributes to warming and causes increased radiation.

If the radiated output of an object is, according to the Stefan-Boltzmann Law $P = \sigma * A * T^4$, where A = the surface of the object, then it is true for the exchange of radiation between two objects that:

$P_{12} = \sigma * k * (T_1^4 - T_2^4)$, where k is the efficiency of the radiation exchange, which depends on the size of the mutually inclined surfaces of the objects and the radiation coefficients ε_1 and ε_2.

Radiation exchange takes place continuously amongst all objects and it theoretically ends only when all the surfaces of the objects have the same temperature.

In the reality of a heated residential space, all heating elements, walls, ceilings, windows, doors, furniture, people, animals etc. function as surfaces which emit radiation. As the heating elements or heating surfaces have the highest temperature and continuously supply this energy, the temperature of all the remaining surfaces would ideally increase until all the surfaces in the room obtain the temperature of the heating surfaces.

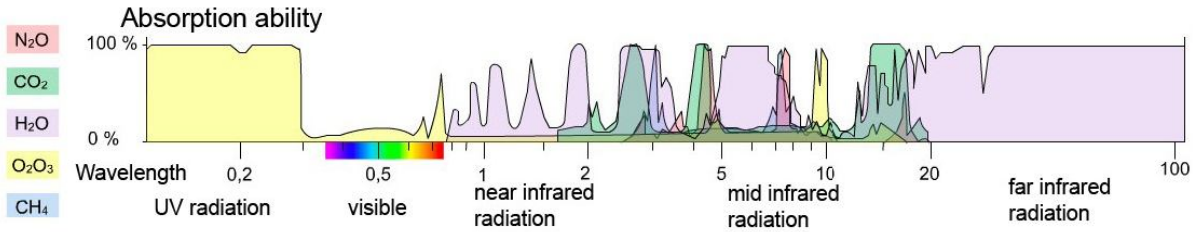
From the whole spectrum of thermal radiation only infrared radiation plays a certain role in heating technology. It is often called thermal radiation in short, even though infrared radiation is actually only one part of thermal radiation.

According to DIN 5031, infrared heating is divided into bands according to the wavelengths IR-A (0.78 μm to 1.4 μm), IR-B (1.4 μm to 3.0 μm) and IR-C (3.0 μm to 100 μm).

Another classification is into near, mid and far infrared radiation, which is usual in the geological sciences (see **pic. 1.4**). Far infrared radiation and IR-C radiation are identical. It is the area of radiation in which the infrared radiation used in this project operates.

Absorption of thermal radiation in the air

Apart from the energy transfer between objects as a result of radiation exchange, energy transfer from an object into a liquid which surrounds it also exists, via the absorption of emitted radiation energy in the liquid. In heating technology, the absorption of infrared heating into the air exists, but it usually has a significantly lower share in the energy transfer than convection.
The degree of absorption in dependence on the wavelength is shown in **pic. 1.6**.



Pic. 1.6: Absorption spectrums of various substances in the air

It can be seen easily that a large amount of infrared radiation can be absorbed as a result of high air humidity.
Apart from that, a permeability "window" in the band of approx. 7μm to 13 μm can be seen in which infrared radiation can spread through the air almost without any restrictions. The absorption zones for ozone, hydrocarbons and nitrogen oxides which are marked here do not play any role in a residential area. The maximum of the used IR-C radiation can be found in this permeability "window" in an ideal situation. Due to the limit at the value of 7 μm, the surface temperature of the radiator shouldn't exceed approx. 120°C. The bottom limit of the surface temperature is set according to the ratio of the contributions of radiation and convection, and it shouldn't be lower than 60 °C (see below).

(Baehr, H.D., Stephan, K.: Heat and Mass Transfer, 4th edition. Springer-Verlag, Berlin 2004)

Feeling of comfort

In heating and air-conditioning technology, '(thermal) feeling of comfort' describes the areas of surrounding temperature and the areas of the state of the air where a person feels the most comfortable. The terms 'thermal sensation' and 'temperature of thermal comfort' have also been introduced.

Thermal sensation and the temperature of thermal comfort

The purpose of a heating system isn't only to facilitate survival while outdoor temperatures are low but also to contribute to a comfortable climate in the room. What are known as thermal sensation and the temperature of thermal comfort are objectively measured quantities and are the subjects of the DIN 33 403, DIN EN ISO 7730 and DIN 1946 standards. The temperature of thermal comfort is a subordinate term to thermal sensation and it is determined by pre-selected, standardized, physiological and individual parameters from thermal sensation temperatures in interiors which, based on the DIN EN ISO 7730 standard, create a level of satisfaction with the climate in a room for at least 90% of a statistically significant number of people. Thermal sensation and the temperature of thermal comfort are dependent on

- the air temperature in the room,
- the temperature of radiation from the surroundings,
- the distribution of air temperature (air layering),
- air circulation (drafts) and
- relative air humidity.

An extensive explanation of this topic can be found in
(Recknagel, Sprenger, Schramek: Handbook on Heating and Air-conditioning Technology, Oldenbourg Wissensch.Vlg; issue 68 (1997/98), p. 50 ff)

Air temperature in a room

The air temperature in a room is a physical quantity which describes the energy state of the air in the room. It is expressed in degrees Kelvin (K) or in degrees Celsius (°C). In the presented report, degrees Celsius are used. Temperature differences are given in degrees Kelvin.
The air temperature in a room indirectly states the amount of thermal energy which can mutually interact with the room surroundings or the objects or people which are located within it. This happens when there is a temperature difference with the air, occurring by heat conduction from the warmer to the cooler side. Physiologically, heat conduction from a human body into the air feels like cooling, and the other direction of conduction feels like warming.

Temperature of radiation of the surroundings

The temperature of radiation of the surroundings is the mean temperature of the surfaces of individual areas which delimit a room (walls, floor, door and window surfaces, surfaces of heating elements). It is composed from the result of the sum of the products from the individual surfaces and their temperatures and the sum of the individual surfaces:

$$t_U = (\Sigma A_i t_i / \Sigma A_i)$$

where:

A_i: surface area of the individual surface i

t_i: temperature of the individual surface i

In relation to thermal sensation, it also presents the level of thermal radiation perceived by a person from their surroundings.

Asymmetry in the temperature of radiation

If the walls in a room have significantly different surface temperatures, this fact can have an influence on the feeling of comfort even though the average temperature of radiation of the surroundings is within the range which is perceived as pleasant. This is called asymmetry in the temperature of radiation. For this reason it makes no sense to use heating surfaces with temperatures higher than 120 °C, because asymmetries are then very prominent. If infrared heaters are located unfavourably, e.g. opposite windows, asymmetry becomes disturbing at as low as approximately 80 °C. Infrared radiators thus should be placed on walls where there are windows or transversely opposite them. When installing them on a ceiling, they should be at a distance of at least 1 metre from the head. It only makes sense to place them in this position in the high rooms that can be found in old residential buildings.

(Report on the Feeling of Thermal Comfort in Residential Areas with Regard to Electric Heating Surfaces, Prof. Dr.-Ing. Bruno Gräff, November 2006;
http://ihs-europe.de/wp-content/uploads/2009/03/gutachten-uber-infraheat-vprofgraff-in-pdf-datei.pdf).
(Research report B I 5 80 01 97-14, Prof. Dr.-Ing. Gerhard Hausladen, Optimization of the Arrangement of Heating Surfaces and Airing Elements by the Simulation of Flow, Gesamthochschule Kassel University, 1999)

Distribution of air temperatures

As far as the distribution of air temperatures is concerned, in inside areas only the vertical distribution or layering of the temperature of the air is relevant for thermal sensation. Horizontal or irregular distributions either don't occur or can be taken into account via the air circulation which occurs due to them.
The term 'layering of air temperatures' means the progression of temperatures with a dependence on the height above the ground. The temperature progression is dependent on the type of heating, thermal insulation and how the room is sealed against the outside air.
The temperature progression should be constant if possible. Investigations (e.g. Olesen, B.W., M. Scholer and P. O. Fanger, Indoor Climate, 36. pages 561/579 (1979) proved that a temperature difference of as little as 1 K per each metre of height is perceived as disturbing.

Air circulation

Air circulation is the movement of all air particles aiming towards a certain point in a room, and it is caused by air pressure differences. It is expressed as the mean speed of air particles in m/s. The situation occurring when air particles are cooler than the surrounding air in the room and movement constantly takes place in one direction has a particularly great influence on the feeling of comfort. It is called a draft.
According to the ISO 7730 and VDI 2083 standards, air flows of under 0.1 m/s aren't disturbing and they have no effect on the feeling of comfort.

Air humidity

Air humidity describes the quantity of water vapour in the air. Because the absorption power of the air for water molecules depends on temperature, there is a distinction between absolute and relative air humidity. The warmer the air, the higher is the absorbable quantity of water. The absolute air humidity is the amount of water for every room volume (g/m^3).

Relative air humidity is the ratio of the current amount of water in the air to the maximum possible amount of water for the given air temperature, and it is given as a percentage. The strength of evaporation of water on skin depends on the relative humidity. Heat is created on the skin by evaporation and is taken away by the evaporating substance. For a feeling of comfort at air temperatures of around 20°C, a relative air humidity of under 30% or above 70% plays a certain role (DIN 1946).

Operative temperature

In practice, the feeling of comfort firstly depends on the air temperature in the room and on the temperature of radiation from the surroundings, and also on the effects of drafts. Therefore, the term operative temperature was also defined in DIN EN ISO 7730, and it expresses exactly these quantities.
(Recknagel, Sprenger, Schramek: Handbook on Heating and Air-conditioning Technology, Oldenbourg Wissensch.Vlg; issue 68 (1997/98), page 54)
(Research report B I 5 80 01 97-14, prof. Dr.-Ing. Gerhard Hausladen, Optimization of the Arrangement of Heating Surfaces and Airing Elements by the Simulation of Flow, Gesamthochschule Kassel University, 1999).

In the simplest case – without the effects of drafts – the operative temperature T_o is the mean temperature of the air temperature in a room, T_r, and the mean temperature of the radiation from the surroundings, T_u:

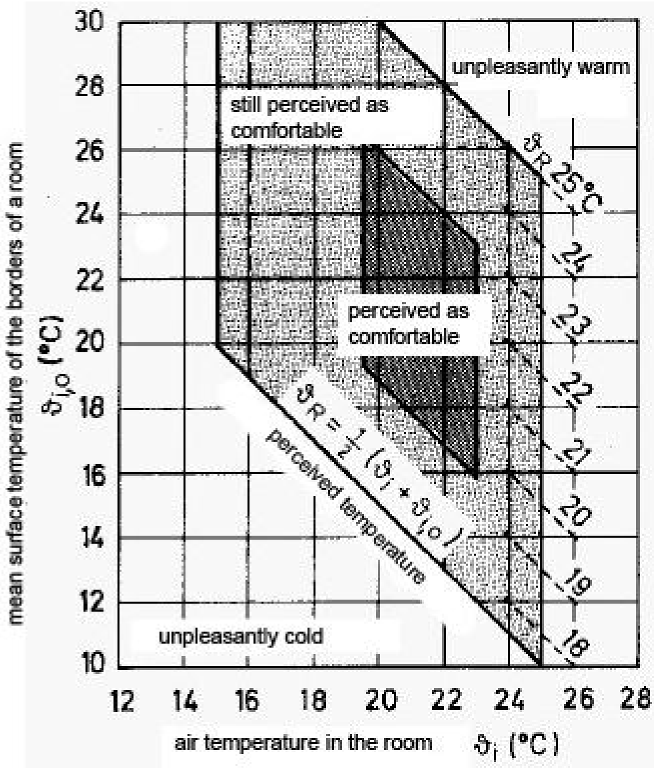
$$T_o = (T_r + T_u)/2 \ .$$

The optimal operative temperature also fundamentally depends on the activities and clothing of people. When doing work while sitting down and in light clothing, an operative temperature of about 21.5 °C is optimal, for example.

When choosing and dimensioning a heating system including the relevant regulation technology, it is enough to fulfil the requirements for the desired achievement of a certain operative temperature. The requirements for air-conditioning devices are higher and all requirements for the achievement of a set thermal sensation temperature have to be achieved; this also includes the regulation of air humidity.

The operative temperature is depicted in diagrams of the temperature of radiation - air temperature in the form of fields of thermal comfort (see **pic. 1.7**).

It is a tendency that higher temperatures of radiation are perceived as more pleasant in contrast with higher air temperatures. Heating systems which create higher temperatures of radiation than air temperatures need to be preferred for reasons connected with the feeling of thermal comfort.



Scope of validity
Rel. air humidity φ_i from 30 to 70%
Air movement v from 0 to 20 cm/s

Extensive equality of temperatures of all surfaces delimiting the room (according to H. Reiher and W. Frank)

Pic. 1.7: Diagram of radiation temperature – air temperature

1.3.3 Medical aspects

Individuals with allergies/ asthma

Mainly individuals who are allergic to dust in the household suffer due to the heating technology used there. Allergy to dust in the home means oversensitivity and allergic reactions to the excreta of mites in dust in the household, which can cause a runny nose, itching and allergic asthma. This reaction of the immune system isn't caused by the household dust itself but by the excrement of mites which live in the dust. This excreta sticks to the dust and is "stirred up" by every form of flow. The lower the amount of flow, the better for an allergic person. Due to its functional principle, infrared heating has the lowest ratio of flow (convection). (Wilfried Diebschlag, Brunhilde Diebschlag: Allergy to Dust in the Household. Medical and Hygienic Aspects, 2nd edition, Herbert Utz Verlag, München 2000)

Medical treatment with heat

Medical treatment with infrared radiation belongs to the field of physical treatment or physiotherapy. Here, we deal with medical forms of treatment which are based on physical principles such as heat, electric current, infrared radiation and UV radiation, the use of water and mechanical treatments such as massage. In particular, the use of IR-C radiation, which is used in infrared saunas, has been well-researched in the areas of treating pain, overstrain of the locomotor apparatus and the treatment of vascular problems. Infrared heating has a positive medical and therapeutic effect. Apart from that, it is a component of radiation which surrounds us in our everyday lives constantly because it is radiated, to a higher or lower level, by all objects anyway.

(Richter W., Schmidt W.: Mild Hyperthermia of the Whole Body with the Help of IR-C Radiation. Z Onkol/J Onkol 34 (2002) 49 - 58)
(Schmidt W., Heinrich H., Wolfram G.: Detoxification and Stimulation of Immunity as a Result of IR-C Radiation. 33(2004)66-68)

1.3.4 Principal flows of energy in heating systems: primary energy, secondary energy, final energy, useable energy

Energy which exists in a free or fixed form, available in energy resources which can be found in nature, is called primary energy, from the point of view of energy management. This category includes the above-mentioned forms of the energy spectrum.

- renewable energy, such as biomass, water energy, solar energy, heat from the Earth (geothermal energy) and wind energy,
- fossil energy, such as brown coal, black coal, natural gas and oil, and
- nuclear energy (uranium).

Secondary energy, or the carriers of energy, is created as a result of the dissipatory processes of transformation, such as burning, nuclear fission or refining. Energy carriers are, for example, gas, electrical energy, petrol, oil or long-distance heating.
The energy which reaches the consumer after possible further losses during transformation or transfer is called final energy.

Useable energy is that energy which, in the end, is available for the end user for direct use or after transformation from the final energy into the form of energy-based service required. Useable energy includes heat, cold, light, mechanical work and acoustic waves.

Useable energy is usually lower than the amount of final energy because the transformation of energy from the final energy involves a degree of energy loss. A bulb, for example, produces both light and heat from the final energy – the electric current. In normal cases this heat isn't used for any purpose.

1.3.5 Division of heating systems according to the sources of energy used

As far as ecological aspects are concerned, it makes sense to divide heating systems according to the sources of energy which are used for the transformation of energy and their origin. From the physical point of view, we can find four different types of energy:

- Chemical energy: solid fuel, oil, gas
- Electrical energy
- Energy from solar radiation
- (Ecological) heat

Energy from solar radiation and (ecological) heat are renewable forms of energy in themselves. In the case of chemical and electrical energy, it depends whether the initial sources of energy are renewable or not. They are often of mixed origin. Thus, the renewable portion of the total electrical energy supply is currently more than 15% and still only a small quantity of biogas – in the order of a few per cent - is added to natural gas distribution, and this differs depending on the location. Solid fuel and oil can be fully produced from biomass and delivered to the consumer.
As the transition towards renewable energies in the energy supply system is generally a relatively slow process taking place over tens of years, the simplest and most complete renewable energy option should be considered when choosing a heating system.

1.3.6 Division of heating systems according to the type of heat distribution

Local heating

The term local heating describes heating in which heat from the provided form of final energy, such as gas, oil, wood, coal or electric current, is produced only in the individual households via independent energy transformers. The source of heat is thus located in the individual rooms and its purpose is to heat the direct surroundings in which it is located, independently of the other rooms. Heat distribution also takes place in the same room. Open fireplaces, closed stoves such as fireplace-style stoves, tile stoves, basic stoves, top-feed stoves with a connected oil exchanger and individual stoves with a gas connection directly in the room are all forms of local heating, as are electrically powered resistance heaters such as heating ventilators, electrically heated radiators, infrared radiators (space heaters), electric floor heating and electric storage heating systems.

Central heating

With central heating, the transformer of the final energy into heat, and thus the source of heat, is located centrally in a building or a complex of buildings. Thermal energy has to be conveyed to the individual rooms first, using suitable media such as water, water vapour or hot air, and then by heating elements or heating surfaces within the room.
The most wide-spread form of central heating in Germany is gas central heating, known as 'warm-water heating', which uses warm water as the carrier medium. After this there is oil central heating, various kinds of heating using thermal pumps, and pellet heating.

In the presented research, gas central heating is compared with a de-centralized heating system consisting of infrared local heating.

Principle of heat transfer into living spaces: convection heating and heating by radiation

This research project uses the term 'heating by radiation' if the heating elements or heating surfaces transfer more than 50% of the amount of energy by radiation. However, this isn't often achieved in practice (see below).

This research project speaks about convection heating if the ratio of energy transferred into the room by convection using heating elements or heating surfaces is more than 50%. Most heating devices which are available on the market use convection heating.

Special notification: Every form of heating element or heating surface transfers energy both by radiation and convection, and usually even a negligible amount of energy in the form of thermal conduction. The mix ratio is crucial. Incorrect or incomprehensible interpretations in leaflets, on internet pages and other publications in the heating field, often create the impression that a "pure" form of heating by radiation or convection exists. However, such a form is obtainable only approximately, in physics experiments at high cost, and it certainly doesn't exist in practice in the heating industry.

Proportions of convection and radiation heating for various heating elements and heating surfaces

The proportions of convection and radiation essentially depend **on the temperature of the surface, state of the surface and the structural shape of the heating element.**

In the case of the simplest structural shape of an independent panel-shaped heating element with one panel, a radiation coefficient approaching 1 and a standard size of approx. half a square metre to one square metre, both proportions are the same for a surface temperature of approx. 60 °C to 70 °C. For low surface temperatures the proportion of convection prevails, and in the case of higher temperatures, it is the proportion of radiation.
In the case of more complex structural shapes, such as articulated heating elements, tubular steel radiators, lamella radiators and panel heating elements with convectors consisting of several panels and metal sheets, the proportion of convection increases strongly due to chimney effects, and for high input temperatures and at 90 °C on the surface, the proportion can reach up to 90%.
On the other hand, the proportion of radiation increases with increasing surface area in the case of a simple heating surface. If the surface area is greater than 10 square metres, equality of convection and radiation heat is already achieved at a surface temperature of approximately 45°C to 50°C.
(Recknagel, Sprenger, Schramek: Handbook on Heating and Air-conditioning Technology, Oldenbourg Wissensch.Vlg; issue 68 (1997/98), pages 435 ff, 938 ff and 836).

1.3.7 Special structural shapes of heating elements and heating surfaces

Tile stoves and fireplaces

Tile stoves and fireplaces without air channels are closest to simple panel heating elements in their behaviour, though their surface area is usually larger as a result of the cuboid shape of the element. As the temperatures on the surface usually reach approx. 80°C, it is a standard form of heating by radiation. However, with tile stoves and many fireplaces with air channels the proportion of convection prevails, as a result of strong chimney effects.

Baseboard heaters

A baseboard heater (also known as a skirting radiator) is a special form of convection heating element. Baseboard heaters usually run along the inner side of outer walls immediately above the floor. The heating elements of baseboard heaters consist of a tube with flowing hot water to which many sheet metal lamellas are attached. As a result of the lamellas, a local chimney effect is created (convection). Baseboard heaters create an air screen from hot air along walls and glass window surfaces. Thus, the surfaces of these walls and windows are heated. The required feeling of comfort is created by the temperature of the radiation from surfaces whose heat is created in this way. Because the screen of warm air is very thin and moves only slowly in comparison with the flow of air from other forms of convection heating, the air inside the room warms up more slowly and its temperature usually remains lower than the temperature of the screen of warm air.
The baseboard heater represents the most highly-optimized form of convection heating. In order for it to become radiant heating, the surface temperatures of the walls or glass surfaces would have to be heated to at least 45 °C by the hot air screen, which isn't the case, however.

Large-surface heating (ceiling, wall and floor heating)

Large-surface heating is usually made from flexible heating pipes, inserted into the ceiling and wall plaster or into the floor screed. This is then always called ceiling, wall or floor heating. The surfaces warm up via heat conduction and thus ensure a pleasant medium temperature of radiation. The air is usually warmed up by slow convection. This is also true when electrically powered heating pipes or heating foils are used instead of heating pipes with flowing water.
Baseboard heaters and large-surface heating are erroneously called radiant heating, even though they usually transfer less than 50% of the thermal energy or electrical energy they bring into a room in the form of radiation. The name actually describes the advantage you gain from these forms of heating, i.e. they provide a high mean temperature to the environment by radiation because the surfaces of the room are partially heated directly, partially by a proportion of radiation and partially using an air screen. Large-surface heating would be ideal if it maintained all the surfaces which delimit the room at a low temperature level of approx. 20 to 25 °C. This would mean that practically no exchange via radiation would take place between the surfaces in the room and the surface of a clothed human body because the temperatures of all surfaces would be approximately the same. It is exactly this is that is perceived as being particularly pleasant. The thermal output emitted to the room by such heating elements takes place mainly by convection and the absorption of radiation into the air in the room.

The advantages are similar to those in the case of real heating by radiation:
- no need for space to mount the heating elements in the inhabited room
- dust doesn't settle on the heating elements,
- lower vertical temperature gradient in the room,
- lower air temperature in the room than in the case of classic convection heating; the result is the physiologically pleasant heating of the people within,
- no or only slight condensation from humidity on structural parts, which prevents the formation of mould.

1.3.8 The role of thermal energy storage mass in heating systems.

Both in local heating and in central heating, thermal energy is stored in the heating system immediately before it is transferred into the room. Depending on the heating systems, these accumulators vary in size depending on their weight. The general rule is: The more mass there is, the larger the heat accumulator is.

Types of storage mass include the water in the heating element as well as the heating element itself, fire-clay tiling in fireplaces and electric heating or screed in the case of floor heating.

In the past, when stoves heated with solid fuel were standard and when no regulated heating existed, the largest possible amount of storage mass was desirable. Fuel was put into the stove only once or twice per day and the storage mass provided uniform heat transfer into the room even when the fire in the stove had already gone out This was also the case for heating with oil or gas without regulation and with simple valves on the heating elements.
If the heat transfer takes place approximately evenly with the creation of the heat, the amount of storage mass doesn't play any role.
It isn't like this in the case of modern heating systems with temperature regulation in rooms and houses with low heating energy requirements. Changing radiation from the sun, the use of supplementary sources of heat (e.g. baking ovens) or the opening of windows makes it vital that the heating regulation can react quickly. The regulation can only prevent or allow the inlet of heat into the accumulator; it cannot prevent or allow the transfer of thermal energy from the storage mass into the room.

In cases when heating should take place fast, there is a large time delay with a large storage mass. For floor heating, which has to warm up the whole volume of screed as storage mass, this delay can be several hours.
In the opposite situation, when the room is heated additionally, e.g. by warming due to the low winter sun through a south-facing window, and the heat supply should be interrupted, the room gets overheated and energy is consumed unnecessarily as a result of the already accumulated warm water for heating in the heating elements. From the regulation and technical aspect, this is called an overshoot, or regulation inertia.

An energy-saving heating system with a regulator should have the smallest amount of storage mass in the heating elements or on heating surfaces, which is against the generally prevalent opinion. The buffer memory of the central heating in the heated room thus remains intact because the heat transfer from here takes place into rooms which are under the control of regulation.

A large storage mass in infrared radiators causes the radiator to remain within a temperature range between the surrounding temperature (air temperature) and 60 °C for a long period after every time it is switched on or switched off by the regulation. It means that the warming up and cooling down times are significantly longer than five minutes instead of being less than one minute, which is the ideal case. During this period, the infrared radiator works as a convection heater. The advantages of infrared radiators disappear with larger amounts of storage mass when such radiators are used. Many such "infrared radiators" are thus only convection heaters with a higher ratio of radiation.
This is also true for electric heating foils installed close to the surfaces of walls. Although they reach high surface temperatures in contrast with standard surface heating, the complete wall works as a reciprocal accumulation mass. In total, they transfer less than 50% of input electrical energy in the form of infrared radiation. When they are installed near a floor, an air screen is also created as a result of large-surface convection, similarly as in the case of baseboard heaters.

(Otto Föllinger: Regulation Technology, Hüthig Verlag)

(Lutz & Wendt: Handbook on Regulation Technology, Verlag Harry Deutsch)

(Fröse, H.-D.: Electric Heating Systems, Pflaum Verlag 1995)

1.3.9 Classification of infrared heating

Heating which meets the following definition is classified as infrared heating: it is local heating, heating by radiation, i.e. more than 50% of the pure share of thermal energy radiation is emitted into rooms, and the maximum amount of radiation is found in the area of infrared radiation (also for heating which radiates a visible component, i.e. glows red).
The transferred radiation of infrared heating corresponds to the natural infrared radiation of solar light below the visible band.

Infrared heating by gas

Infrared heating by gas or so called space heaters is used with heating gas, usually the liquid type, in industry and during camping, in stationary use also with natural gas but this is more uncommon. The gas flame heats the heating envelope. Industrial space heaters can be used as the sole heating source for halls. Special safety measures have to be obeyed for gas space heaters. Because of that, they are not suitable for use in residential areas. In recent years, terrace radiators (which are also called "mushroom heaters") have started to be used more and more in outdoor areas such as street cafes. These aren't suitable for residential areas either.

Infrared heating by gas is a form of high-temperature radiator heating in which heating energy is created by the structural part of the radiator or in it, and it is radiated at a high temperature (from several hundred to over a thousand degrees). This form of heating is used to transfer thermal energy over larger distances or to a larger degree. As a result of the high temperatures generated, there is a danger of fire which has to be kept under control with the help of safety measures.

Electric infrared heating
Electric space heaters, quartz radiators, radiators without a filter

Electric space heaters are also high-temperature radiators and operate on the same principle as a bulb but usually with a resistance wire wound on a ceramic carrier which is heated up by electric current. In most space heaters, the maximum radiation is in the IR-B radiation range, i.e. they radiate a dark red colour. So-called quartz radiators are a special case. Their maximum radiation is in the IR-A radiation range, their radiation is bright red and the glowing spiral is surrounded by a quartz tube so that the radiation can penetrate as well as possible. Quartz radiators have the highest proportion of radiation (95%) of all infrared radiators. Infrared radiators, the maximum radiation from which is in the IR-A or IR-B range, are also called filter-less radiators because their radiation is visible.

Radiators with a filter

An infrared heater with its maximum radiation in the IR-C radiation range is called a radiator with a filter because no visible component is emitted as light. Radiators with a filter are powered both by gas and electricity. A special form of radiator with a filter is electrically powered surface infrared heating. The temperature of its surface doesn't usually reach 150 °C. Both of the most frequent structural shapes are made of metal with an integrated heating spiral, and those which use carbon foils through which electric current flows are hung on a frame.
This form of surface infrared heating is used in the presented research.

Efficiency of radiation
The efficiency of radiation described in the DIN EN 416-2 and DIN EN 419-2 standards, as well as in directive (90/396/EHS), is valid for infrared heating powered by gas. Both are decisive for the rational use of energy and for economy, while the aim is to achieve an efficiency of radiation (corresponding to the proportion of infrared radiation) which exceeds the value of 50% by as much as possible.
For electrically powered infrared heating, it is necessary to analogically use the efficiency of radiation as a ratio between the output of the infrared heating and the supplied electric wattage, though of course no standard exists for this yet.

2 Related work

Specialized scientific literature dealing with the use of infrared heating in residential areas is almost unavailable because it isn't commonly used as a main form of heating here.

Typical examples of use of infrared heating have been, up to now, large functional buildings or half-open buildings such as production or storage halls, exhibition buildings and buildings for events, washing halls, sports and riding halls, airplane hangars, agricultural areas with stables or greenhouses, churches and football stadiums. The main reason for their use was the targeted heating of workplaces without the energetically demanding complete heating of the air in the room.

There have been numerous, also company-led studies of the use of infrared heating powered mainly by gas in such buildings, and corresponding research on workplaces, e.g. by specialized professional organizations. The results of such, in parts very detailed, research can unfortunately only be transferred to residential areas with great limitations because a completely different profile of use applies here. In particular, no well-researched statements about the use of energy can be utilized. On top of this, only electrically powered radiators with a filter can be used in residential areas as the main source of heating.
What both of these areas have in common is the use of means to prevent the heating of air, which can bring potentially similar energy savings for homes as in the case of functional buildings.

Various companies offering infrared heating for apartments have carried out research on energy consumption before the refitting of a residence with infrared radiators and after it. However, usually only the consumption of final energy was compared, which only has a certain value when used for direct comparisons with other electrical heating. However, we are talking about energy consumption savings of up to 70%. A disadvantage of such studies is also the fact that they are limited to a choice of certain buildings, and also the values of the previous/subsequent comparison can be altered significantly by a change in the behaviour of the inhabitants and different weather situations.

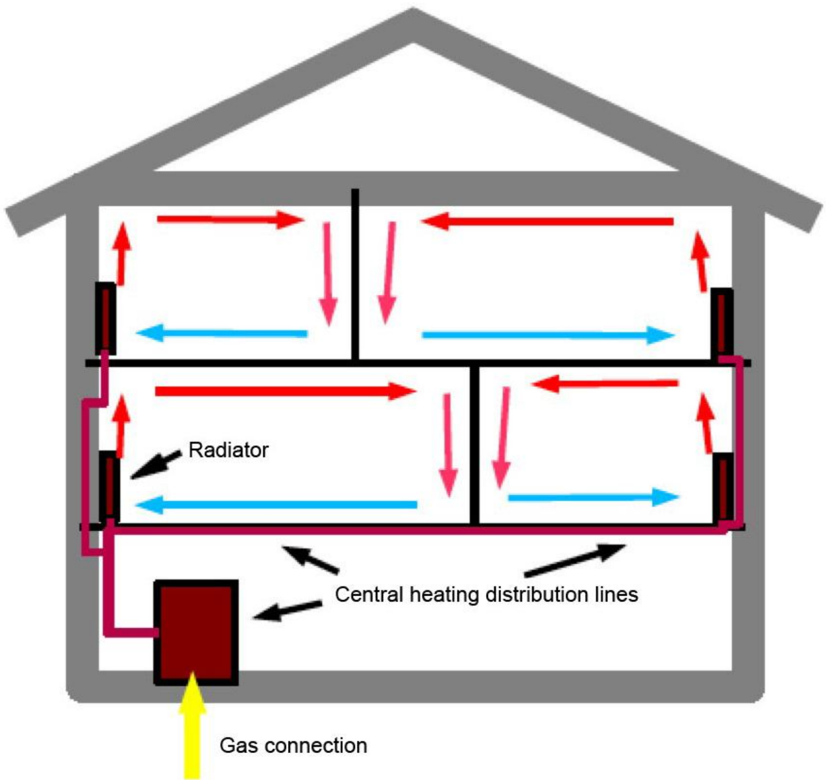
Among these studies, there doesn't seem to be an equally long-term set of measurements at the same place, with comparable behaviour of the inhabitants and the same structural substance, and which limits the above-mentioned disadvantages, as is the case with this study.

3 Research strategy

In order to find the answer to the above-mentioned questions, suitable objects of research were first determined at the abstract level. These comprised gas heating systems (central warm-water heating) and infrared heating.

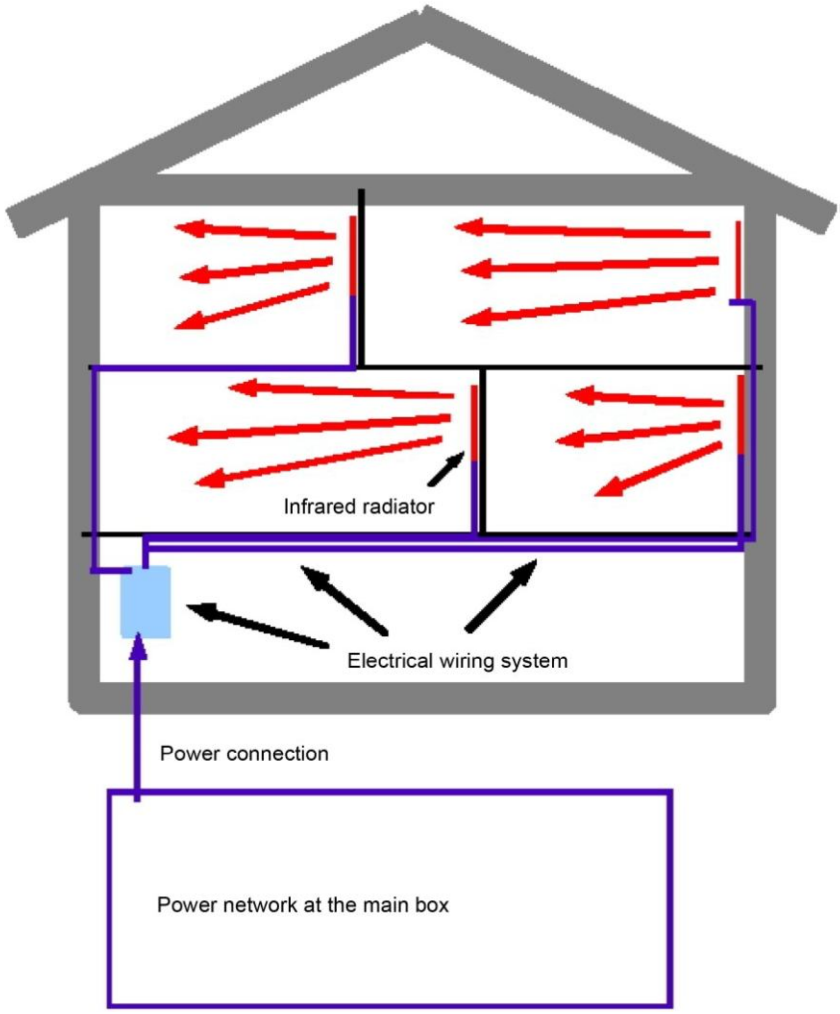
3.1 Monitored systems

Gas heating system:
The most widely used gas central heating structure operated in old residential areas was chosen, with its central gas burner in a non-heated cellar space, circuits with heating water leading into individual rooms and radiators regulated with valves. In principle, the results are transferable also to oil heating, which is the same as far as the structural form is concerned.
The carrier of primary energy, and simultaneously the final energy, is natural gas, which is supplied to the house via gas pipelines. Losses during transport from the gas plant to the house's gas connection are ignored. The useable energy is the thermal energy transferred into the air of the inhabited areas via convection **(see pic. 3.1).** The flow of air created in this way creates a large temperature difference between the top and bottom parts of rooms.



Pic. 3.1: Principal structure of central heating via gas and warm water

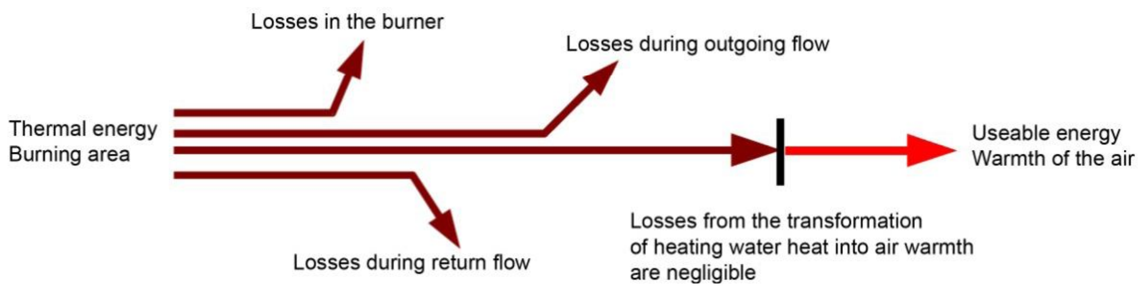
Infrared heating system
Flat infrared radiators are placed on the walls of the rooms in a de-centralized way, like freely hanging pictures, and they are connected via the electrical wiring system. Installation onto a ceiling, in a similar way as with surface lighting, is also an alternative (though it isn't built into the ceiling!).
The partially public power network is also part of the system at the main box (**see pic. 3.2)**. The carrier of primary energy in the joint network is an average combination of the carriers of primary energy for the supply of electrical energy.
The useable energy is the energy from infrared radiation, transferred into the inhabited area.



Pic. 3.2: Principal structure of infrared heating

3.2 Comparison of energy flows

The flow of energy in the gas heating system is shown in **pic. 3.3.**

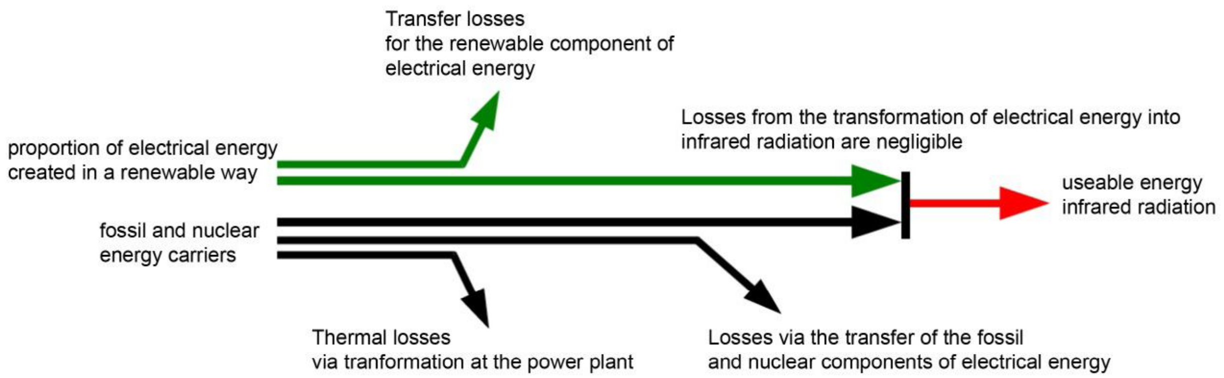


Pic 3.3: Flow of energy in gas heating

The carrier of primary energy – natural gas – is simultaneously the final energy when it is supplied to the house. During burning in the burner, it transforms into approx. 10 kWh of thermal energy for every cubic metre of gas. Part of it enters the circulation of heating water via the heat exchanger, while the rest is lost from the burner via the cellar space or chimney in an outward direction.

The pipes in the heating water circuit leading from the burner to the radiator and back are laid in the walls and ceilings and are more or less insulated, and they heat the surrounding material from the inside. A small portion of thermal energy thus enters the room directly via the walls, ceilings and floors. A substantially larger part, however, gets lost through the outside walls because the temperature difference towards the outside is the greatest in the winter. Apart from that, so called heat leaks cause cooling in the outward direction in old residential buildings. Heat loss occurs in the heating water circuit both during the flow outwards and back. The remaining thermal energy is transferred into the air in the room as useable energy via the radiators. The radiation heat, which is simultaneously given off from the radiators (infrared radiation), can be ignored because it makes up only a few per cent of the total thermal energy transferred and it also heats the air in the room. The objects in the room and the surfaces which delimit the room (walls, ceilings and floors) warm up via the convection (flow) of air in the room. Therefore, the temperature of the air in the room is usually higher than the surface temperature. In old residential buildings, particularly where the burners are old, losses can occur due to bad insulation to the extent that less than half of the primary energy remains in the air of the room as useable energy.

The flow of energy in the infrared heating system is shown in pic. **3.4**.



Pic. 3.4: Flow of energy in infrared heating

The primary energy in the power network is divided into current which is produced in a renewable way, and fossil or nuclear energy carriers. Division into different renewable energies isn't carried out because it doesn't play any role in further assessment.
Electrical energy and thermal energy are obtained from fossil and nuclear energy carriers, though the thermal energy is usually given off into the surroundings unused as waste heat.
On average, 10% of created electrical energy is lost during transfer between the power plant and the main box of the house.
In a house, the incoming electrical energy is transformed into heat radiation energy (infrared radiation) in infrared heaters as useable energy and it is radiated directly into the inhabited spaces. Direct heating of air, as is the case with radiators, can be ignored. Relatively little convection is created. Infrared radiation warms up mainly the wall surfaces, ceilings and floors and objects in the room. A small part of infrared radiation is absorbed by the air and heats it directly. Otherwise, the air is heated indirectly with the help of the surfaces onto which the radiation falls, via large-surface, exceptionally weak convection. Therefore, the surfaces in the room are usually warmer than the air.

3.3 Research hypothesis

The most important difference in both flows of energy is that in the case of infrared heating, there are no losses between the home's main box and the final energy produced. Apart from that, infrared radiation is more suitable than heated air for providing a comfortable temperature in the room (the key word is "operative temperature").

The costs of the form of energy which is being supplied (final energy) are created at the home's main box. It is expected that a significantly smaller amount of energy, measured in kWh, is needed for the creation of comfortable warming in a room in the case of infrared heating, in comparison with gas heating. This could mean that as far as operating costs are concerned, infrared heating is equally expensive or even cheaper than heating with gas, taking into consideration the current development of prices.
At the same time, infrared heating could have the same balance of CO_2 or even better, despite the inclusion of losses from the power plant in the interlinked network.
These conditions were monitored extremely closely in the current project. The aim of the project was to try to answer as many general questions as possible while keeping the costs associated with the experiment as low as could be (see motivation). It was intentional that answers to more specific questions such as e.g. the influence of various structural shapes of infrared radiators etc. were not sought.

After the abstract determination of the system, a specific building to be measured was sought in which, as far as possible, both systems could be compared at the same location, with the same inhabitants and the same building stock. With these requirements, it was possible from the beginning to minimize many aspects which are hard to track and influencing factors such as dependence on the weather, differences in user behaviour and different influences of the building stock (insulation, cumulative behaviour etc) and their varying impacts on the result of the research.

3.4 The measured building

The measured building is a house for two families, with two and a half floors, a typical non-insulated old structure, built in 1930 with sandstone walls. Further structures were added in 1955 and heightening of the house took place in 1967, with the same thickness of walls and building materials. The cellar ceiling and the floor are not insulated.

Partial renovation was carried out at the beginning of the 1990s with the insulation of the roof using wooden tiling (12 cm mineral wool with laminated aluminium foil) in a converted loft area (a room, height of backing approx. 40 cm) and the installation of windows with insulating glass throughout the whole house. The flats are connected by an enclosed staircase.
Since 1993, the building has been equipped with low-temperature gas heating with corresponding heating bodies, insulated with heating pipes and separate heating circuits for each flat. The results of heat requirement calculations are the same values for every square metre for both flats. The consumption to date was measured by a heat meter.

The ground floor flat takes up 102.6 m^2; the flat on the first floor, directly accessible via the staircase and a hall, takes up 160.7 m^2 of the heated area, including the built-up loft area. The ground floor and the first floor have the same floor plan and the same number and size of windows (see below)
Both flats were used by the same family. During the studied period three inhabitants were regularly present.

3.5 Structure of the experiment: installation and measuring devices

In the ground-floor flat, complete infrared heating was installed consisting of the following components:
Various infrared heating devices see floor plan below.
They are electrically powered radiators with a filter with surface temperatures of between 80°C and 120°C.

For every room:

FS20 STR2 radio thermostat and FS20 ST2 switching socket

Devices for the measurement of current consumption:
ENERGY CONTROL 3000 USB (VOLTCRAFT, www.conrad.de),
ENERGY SENSOR ES-1 (VOLTCRAFT, www.conrad.de).

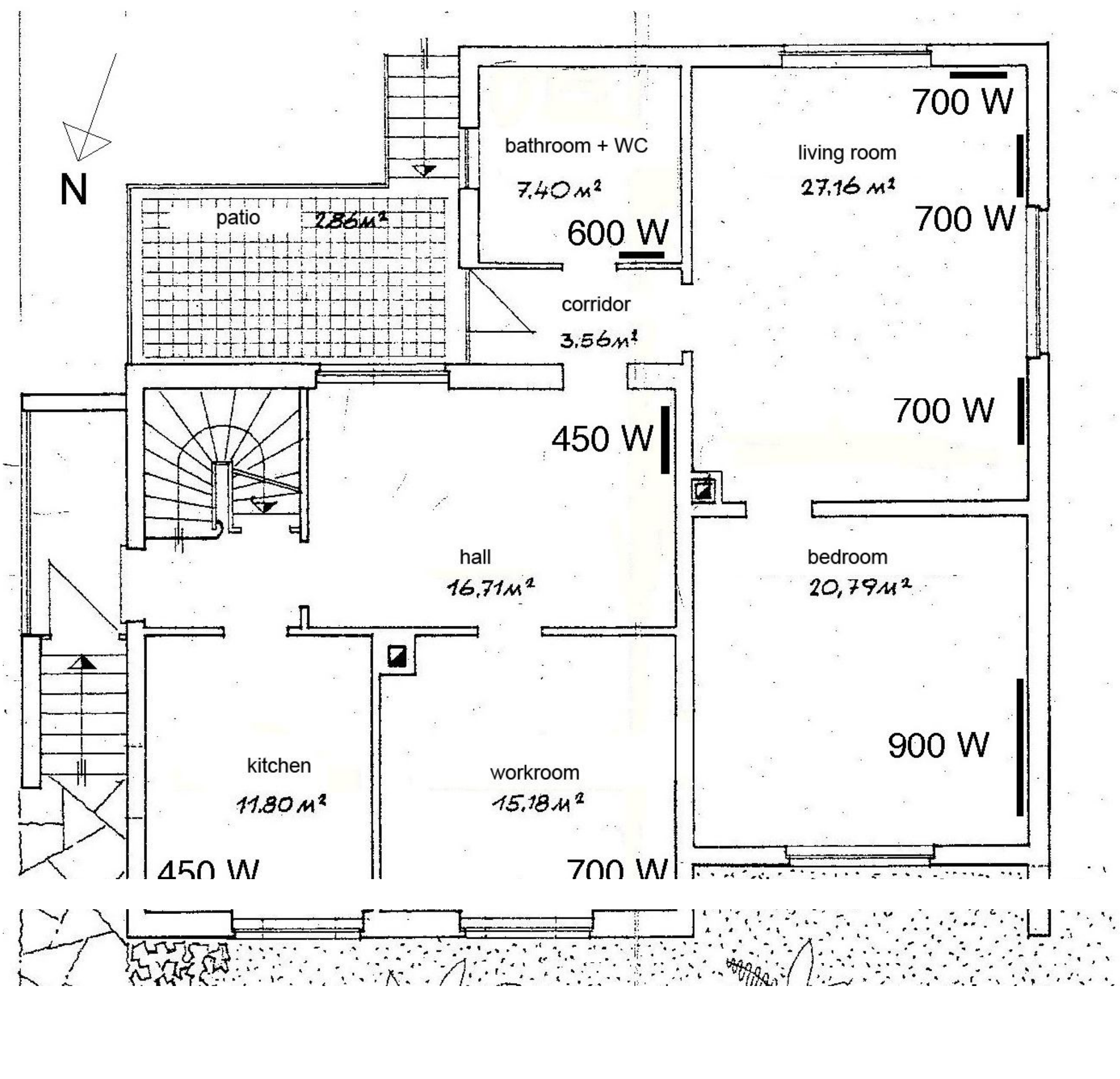
The surface infrared radiators were installed in a decentralized way on the basis of resistance foils without a storage mass, in a similar way as pictures are hung on the wall in rooms, and they were connected to standard sockets of the electric wiring system. Simultaneously, the loading capacities of the individual current circuits were taken into consideration and new wiring (on the wall) was installed if needed.

Radio-controlled switches (FS20 ST2) controlled by radio thermostats (FS20 STR2) were placed between the infrared radiators and the sockets. The transferred infrared radiation is in the longwave IR-C range (see above), without a visible component. The thermal storage capacity of these surface infrared radiators is so small that no danger of burning arises when they are touched for a short time. In order to avoid problems with the accumulation of heat, they mustn't be covered or placed behind curtains.

The locations of the infrared radiators with their power supplies are drafted in in pic. **3.5.** The locations were selected in such a way that they simultaneously:
- provide uniform "coverage" of the room

- prevent asymmetries during radiation
- compensate for the relative small radiation temperature of the window surfaces and
- avoid direct radiation of the window surfaces (from which there is the biggest loss of heat).

The window glass is transparent for visible light and shortwave infrared radiation. For longwave infrared radiation (the band of thermal radiation used by the infrared radiators), it is also impermeable (similar to a black window pane in the visible area). This dependence of the transparency on the wave length is e.g. decisive for the so-called greenhouse effect (the fact that the window glass is almost impermeable for UV light doesn't play any role in this context). Infrared radiation thus cannot leave the room via the windows, but is absorbed by the window panes to a large degree depending to the angle of incidence of the rays (as in the case of walls), and it warms them. The rest of the unabsorbed infrared radiation reflects into the room. Heat loss then appears, as in the case of walls, due to the losses by penetration and radiation from the outside surface of the inside glass pane (for the insulation glass used here) and it is higher – for its surface area - due to the worse insulation values compared to the outside walls. As the absorption increases with the increasing angle of incidence (it is highest in the vertical state), the direct incidence of rays on the window panes should be prevented.



Pic. 3.5 Floor plan of the ground floor of the measured building

The relevant photos are presented in the appendix.

The radio-controlled thermostats are arranged in such a way that they are directly reached by the rays from infrared radiators (“contact by view”) and so that they tend to function as so-called global thermometers used for the measurement of operative temperature.

The devices for the measurement of electricity consumption were installed two-fold in order to achieve redundancy against data loss. The installed infrared radiators were combined into four groups according to the rooms for the purpose of measurement:

Group 1: Bathroom,
Group 2: Bathroom/hall,
Group 3: Office/bedroom,
Group 4: Living room.

The measured values are displayed for these groups in the evaluation shown below.

Supplementary measurements of the temperature of the air and the surfaces of the walls using mobile measuring devices (the AZ 8703 digital thermal hygrometer for the measurement of temperature/humidity and the model ST-8838 infrared radiation thermometer from ELV) were carried out regularly (at least once a week on the days when the gas consumption was recorded) in order to check whether the average temperatures of the surfaces of the walls are higher than the air temperatures in the rooms which are heated by infrared radiation.

The flat on the first floor hasn’t changed fundamentally, as far as the installation and technical properties are concerned. Shortly before the launch of the project, one new circulation pump was installed and the heating circuit was adjusted hydraulically. The heating circuit of the basement flat was shut down.

Heating of drinking water was carried out using gas heating in both flats.

3.6 Test operation

The installation was carried out according to plan in October 2008 and measurement was begun. First, an experiment was carried out during test operation to see if the same air temperature could be maintained in both flats. This wasn’t successful because of differences in the subjective perception of comfort at the same air temperature. As soon as the temperatures set on the thermostats and measured in the air were the same, either the flat heated with infrared radiation seemed subjectively too warm when the heat at the other, gas-heated flat seemed pleasant, or the gas-heated flat felt too cold while the flat heated by infrared radiation was pleasantly warm.

The reason lies in the different principles of heating. The feeling of comfort is simultaneously dependent on the temperature of the air and the average temperature of the surfaces of the walls and the windows (see above).
Therefore, the thermostat settings were changed repeatedly until the same level of comfort was perceived in both flats during the test operation up to mid-November 2008. As both flats were used by all members of the same family, there were no differences in the behaviour of the users.
For the same subjective feeling of comfort, the air temperature in the rooms of the flat which was heated by infrared radiation could be set to 1 to 2 degrees less than in the corresponding rooms of the flat which was heated by gas.

4 Results and evaluation

After the period of test operation, the beginning of the measurement period was set at 16th November 2008. A back-up measuring system for infrared heating was brought into operation on 26th November 2008 so that all the measured values were recorded twice in order to be sure of their accuracy.

The recorded measured data for infrared heating was transferred regularly from the data registration device to one database in two separate notebooks with the help of relevant software, and back-up copies were also stored.
As the infrared heating was connected to the electrical socket circuits, a standard current measuring device was used for the purpose of monitoring. Simultaneously, the gas meter values were recorded, and to check these values, a device was used to measure the amount of heat for the heating circuit for the flat on the first floor. However, the calibration of this measuring device was out of date and therefore it could only be used to provide rough information back-up in order to avoid mistakes during measurement reading.

The period of measurement ended on 30th April 2009. Afterwards, the processing and evaluation of data started.

When processing the data, the values of consumption from both sets of data for infrared radiation were checked as far as accuracy is concerned, and checked with regards to the values of electricity consumption in the household to ensure credibility.

Where it was relevant, the values of readings of the gas measuring device and heat measuring device were processed.

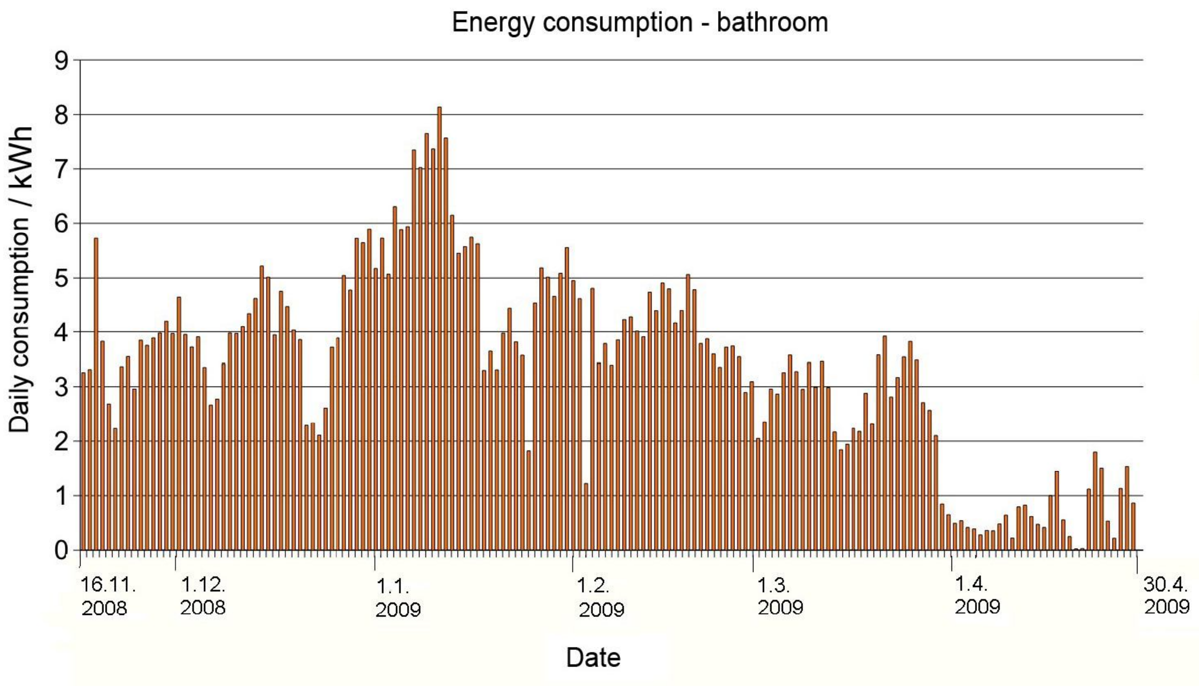
All the confirmed values of measurements were subsequently transferred to a chart calculation programme for further processing.

4.1 Results of the measurements

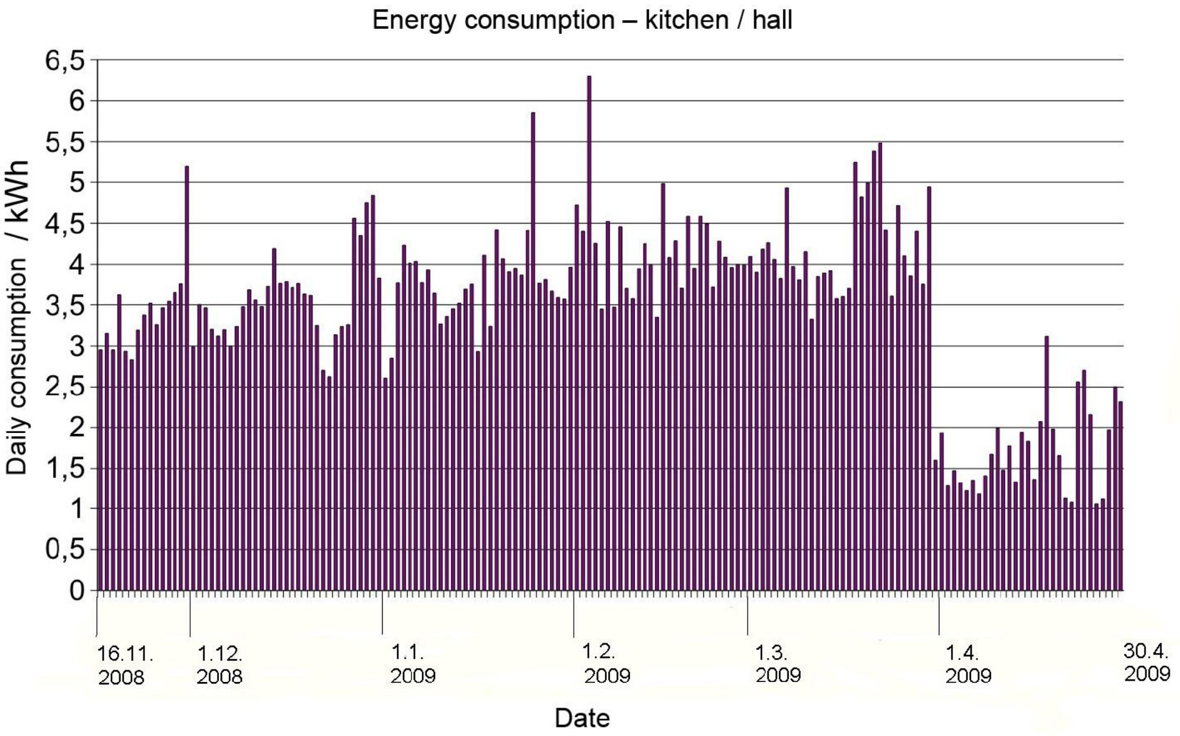
The graphically adapted results of the measurements and the sums of consumption for the whole measurement period are presented in the text below. Detailed chart values are attached in the appendix.

Energy consumption of infrared heating

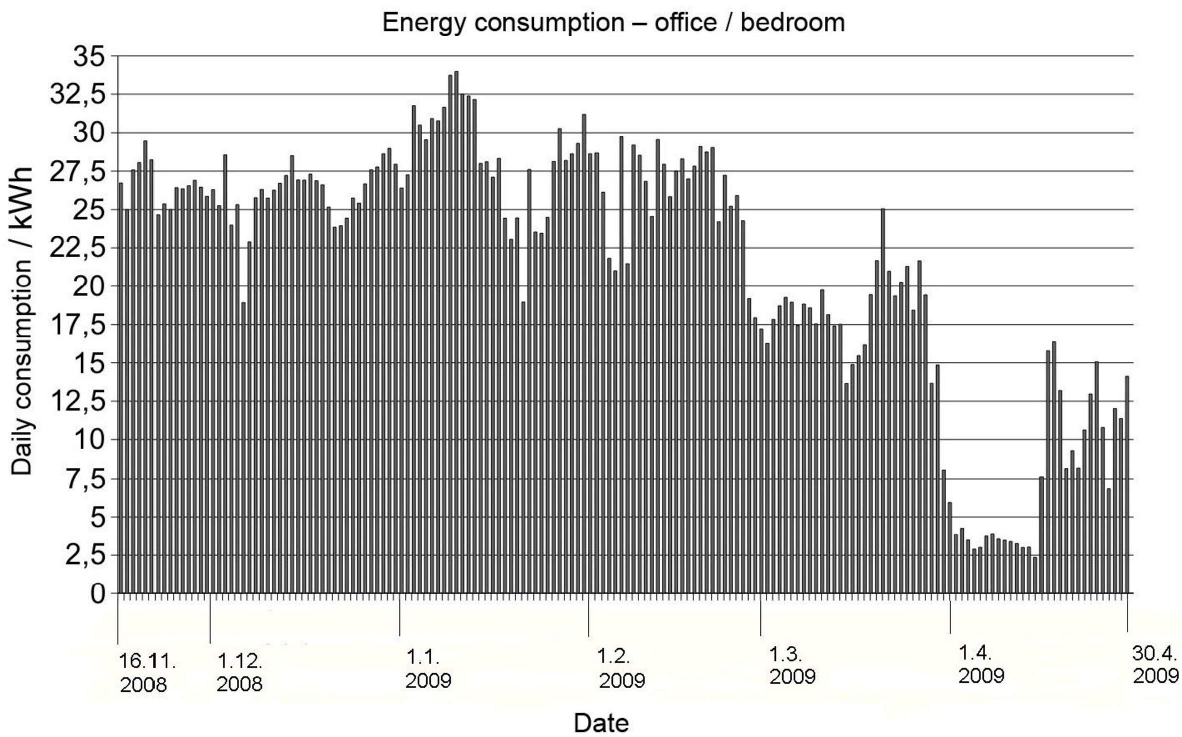
The following graphs show the consumption for the individual groups of rooms.



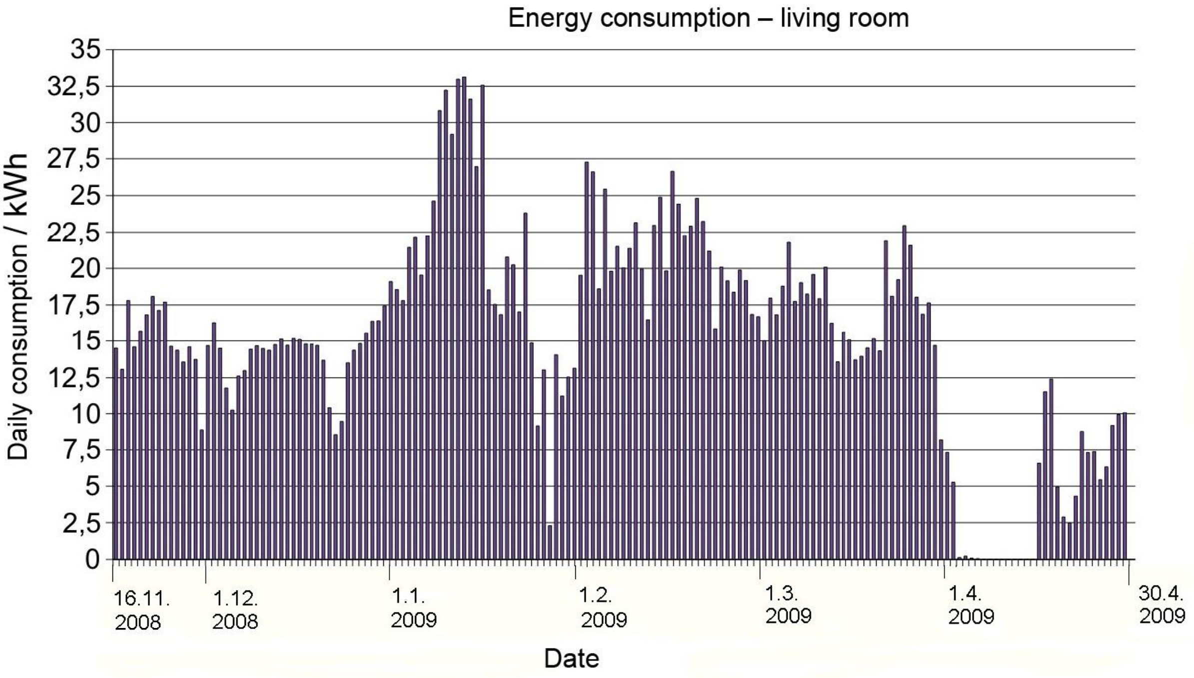
Pic. 4.1: Energy consumption of group 1 (bathroom)



Pic. 4.2: **Energy consumption of group 2 (kitchen / hall)**

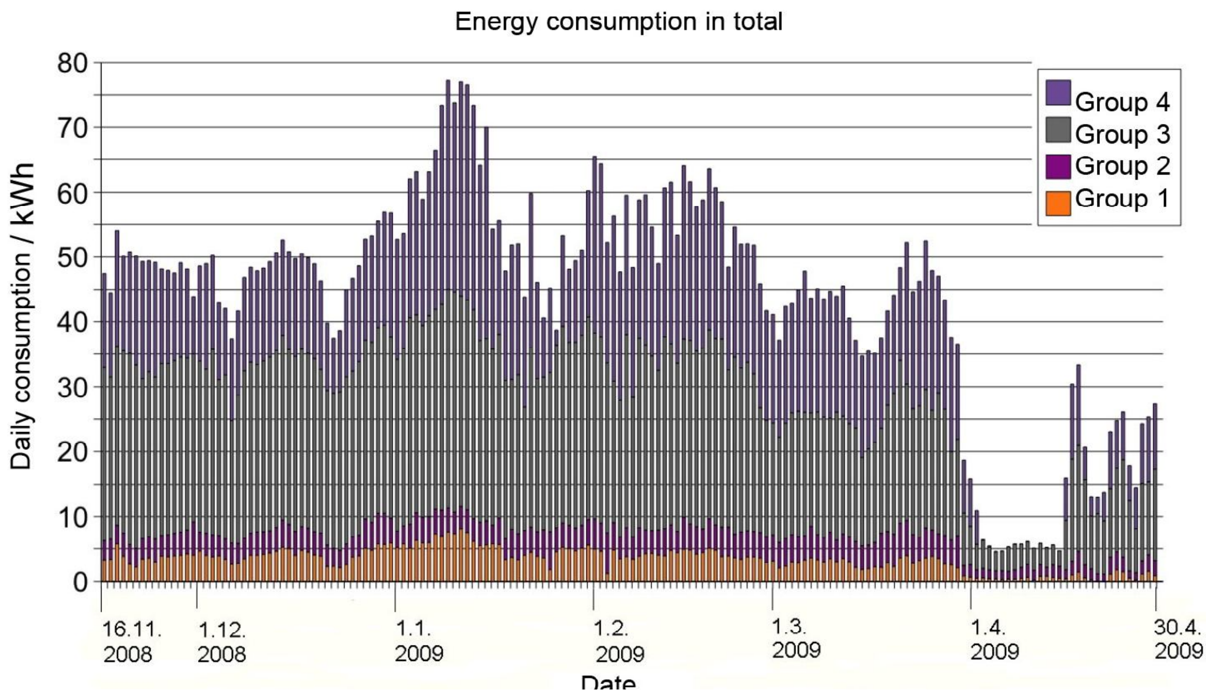


Pic. 4.3: **Energy consumption of group 3 (office / bedroom)**



Pic. 4.4: **Energy consumption of group 4 (living room)**

In **pic. 4.5**, all groups are depicted with their daily sums.

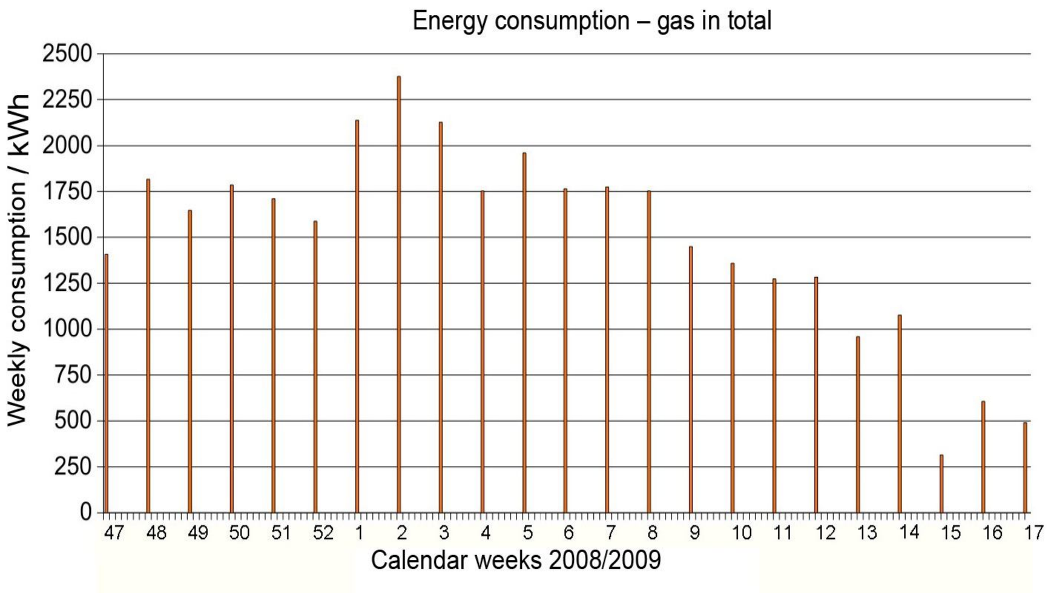


Pic. 4.5: Total daily energy consumption for all groups

The total consumption of infrared heating for the whole complete period of measurement was, after adding it up, **7305.92 kWh.**

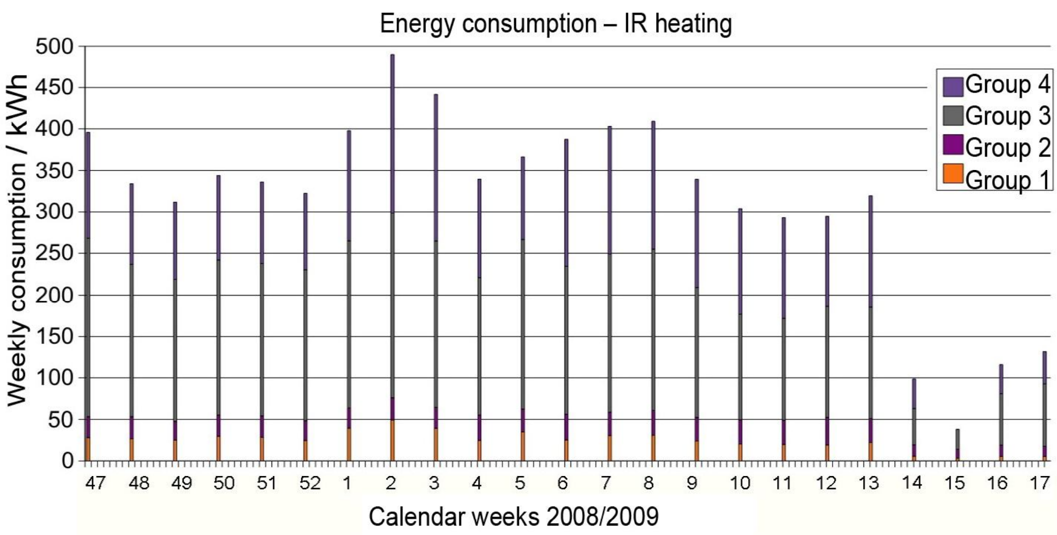
Energy consumption of gas heating

The energy consumption of gas heating was recorded every week by the gas measuring device. The amount of gas used was converted to energy using the coefficients stated by the inhabitants. This is depicted in **pic. 4.6**.



Pic. 4.6: Weekly energy consumption of gas heating

For comparison, the weekly energy consumption of infrared heating is shown in pic. 4.7.



Pic. 4.7: Weekly energy consumption of infrared heating

The total consumption for gas heating for the complete measured period was **34742.33 kWh.**

Separate measurement of the amount of energy needed for the heating of drinking water would have placed significant requirements on the installations, and therefore they were abandoned. As warm water was mainly used for showering, a flat amount of 400 kWh per person for the period of measurement of 5.5 months (standard values including water for bathing are between 800 kWh and 1000 kWh per person a year). Thus a consumption of 1200 kWh arises for the inhabitants regularly present.

The adjusted total consumption for gas heating for the measured period was thus **33542.33 kWh**.

In order to enable a comparison with today's state of heating technology, the adjusted total consumption was reduced by a further 10%. This corresponds to the value of consumption which would be achievable using a gas condensation boiler for heating in the measured building.

The total calculation of consumption in the case of heating by gas using condensation heating technology was **30188.1 kWh** for the measured period.

4.2 Comparison of total energy consumption for the studied period

This consumption is related to the given floor space (of the living area) so that there is a basis for the comparison of energy consumption.

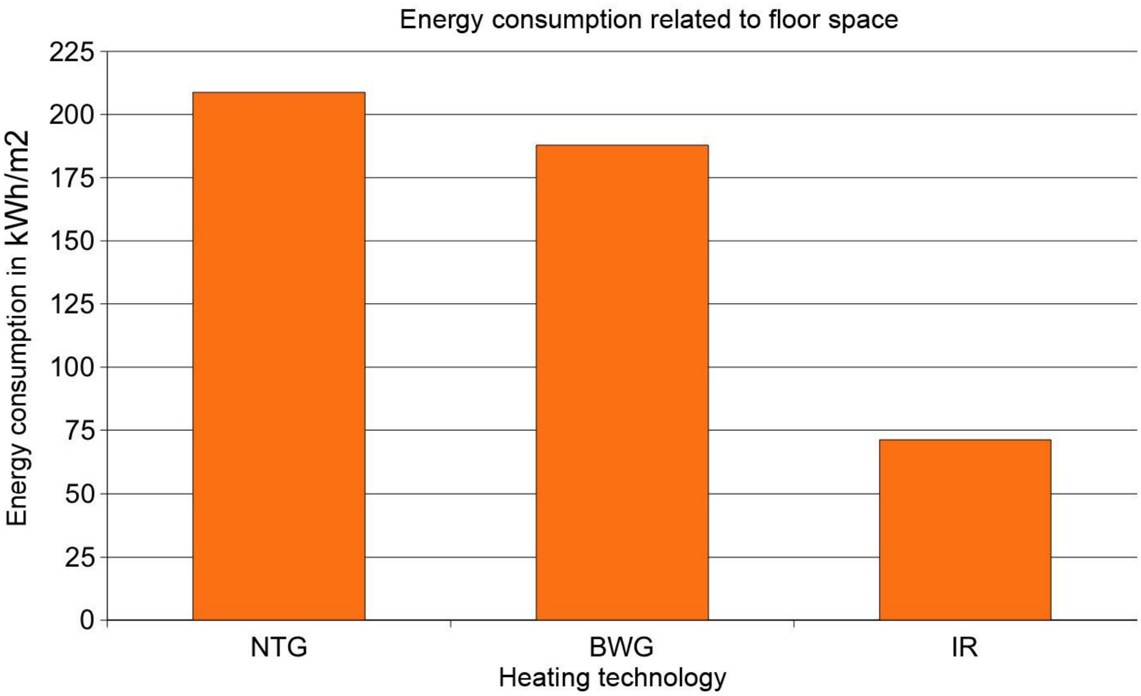
In this way the following result is achieved:

The total consumption of infrared heating related to the floor space in the period of measurement was 7305.92 kWh/102.6 m^2 = **71.21 kWh/m^2**.

The adjusted consumption of gas heating related to the floor space in the period of measurement thus was 33542.33 kWh/160.7 m^2 = **208.73 kWh/m^2**.

The calculated total consumption for gas heating using condensation heating technology related to the floor space in the period of measurement thus was 30188.1 kWh/160.7 m^2 = **187.85 kWh/m^2**.

The values of consumption related to floor space are shown in **pic. 4.8.**



Pic. 4.8: Comparison of energy consumption related to floor space

In relation to low-temperature heating with gas (NTG), the final energy consumption of infrared heating (IR) is only 34.1% of that used by gas, and in comparison with gas heating using the technology of condensation heating it is only 37.9%. This means that the consumption of final energy using gas heating is more than 2.5 times higher than that of infrared heating.

5 Interpretation of the results

5.1 Interpretation from the point of view of energy consumption

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Despite the information about various producers and their internal investigations, which were considered to by tendentious at first, and on which basis the hypothesis of the research was created, the difference in the consumption of final energy is surprisingly marked. As systematic mistakes were practically ruled out by the choice of building and the organization of the measurements, and because the inhabitants cooperated well in order to provide a reliable result (without any changes in the behaviour of the users during the period of measurement), the results of the measurements can be taken as typical for old residential buildings.

Differences can be perceived in the following areas:

a) Losses during transfer between the gas burner and the heating elements, losses in the electrical wiring are negligibly small.

b) Losses via the regulation (as a result of inertia) of gas heating and in the storage mass of the heating elements. While some of the gas heating elements needed more than 10 minutes from when the valves were opened until they warmed up, and after their (manual) closing they heated for at least 30 minutes extra, the warming-up period of infrared radiators was less than 4 minutes (to at least 60 °C) and the period of cooling (from 60 °C to less than 30 °C) less than 7 minutes. The decisive fact was that the period during which the infrared heaters worked as convection heating was as short as possible. Apart from that, the overall concept of the regulation of infrared heating as the regulation of individual rooms without an outdoor temperature sensor is substantially more flexible than the gas heating concept.
The high speed of regulation can be seen clearly in the low consumption of the south-facing living room on cool or cold but mainly sunny days at the end of January and in the transition period at the beginning of April. The prevention of losses by regulation is one of the main advantages in comparison with all other forms of large-surface heating where the inertia is even greater than in the case of radiators. It is probably impossible to achieve desired final energy savings with these means of heating, despite the lower temperatures of the outgoing flow.

c) Various losses by airing as a result of different air temperatures in the room. Both flats were aired in the same, disciplined way by airing them together and for the same time period.

d) Heat losses by transfer (dry/damp wall): heat losses by transfer due to damp walls are high in practice. The low temperatures of the inner sides of outer walls during freezing outdoor temperatures mainly affects non-insulated walls due to their low levels of insulation against dampness. Sample measurements in the gas-heated flat showed that the temperature on the surface of the inner side of the outer wall can reach 14 °C, approximately. The surfaces of the walls which are heated by infrared heating were maintained at a temperature of around 19°C, and their average temperature was always higher than the air temperature. As a result of the high surface temperatures, the absorption of water vapour by the walls was also prevented to a maximum degree.

Also, measurements from different projects showed a significant difference in the drying of walls and maintenance of dryness in houses where a water vapour barrier coating had been applied to the inner sides of the outer walls. The temperatures on the surface of the walls remained closely (ca. 1 K) below the air temperature.
(see www.hygrosan.de)

Insulation values for a damp wall are drastically lower in comparison with a dry wall. A humidity of 4% already lowers the insulation value by approx. 50%. By drying the outer walls via infrared radiation (the drying of buildings is a standard application for infrared radiators), the insulation value probably increased to such a degree that the increase in losses via transfer as a result of the larger temperature difference between the inside and outside surfaces of the outer walls was more than balanced out.

(Ernst Vill: "Wall Humidity – Causes, Implication, Solution", Verlag - Ernst Vill, Sauerlach 2002)

5.2 Interpretation from the point of view of costs

The cost of electrical energy

As a basis for comparison, the standard tariffs, available country-wide, of the four "typical" supra-regional suppliers of electrical energy: EnBW, EON, RWE, Vattenfall, and of the four providers of ecological energy which operate throughout the whole country: EWS, Greenpeace Energy, Naturstrom, Lichtblick, all with 100% certified renewable electrical energy – were used. The numbers can vary locally in the upwards or downwards direction, depending on the available supplier.

The lowest standard tariff (price in force for 4000 kWh – for the summer of 2009) was 19.5 cents/kWh; the highest was 23.8 cents/kWh. As the basic fees of all of the eight suppliers were approximately the same and negligible with regards to the scope of the prices currently employed by the suppliers, they weren't taken into consideration when costs were compared.

The costs of gas

As the four energy providers EnBW, EON, RWE and Vattenfall also operate in the market as subjects who sell gas, their standard tariffs which are available all across the country, were also used as a basis for comparison. Here also the numbers can locally vary in the upwards or downwards direction, depending on the available provider.
The lowest standard tariff (price in force for 20.000 kWh – for the summer of 2009) was 5.0 cents/kWh; the highest one was 5.9 cents/kWh. As the basic fees of all four providers (see above) were approximately the same and negligible, they weren't taken into account when costs were compared.

Development of the prices of electricity and gas

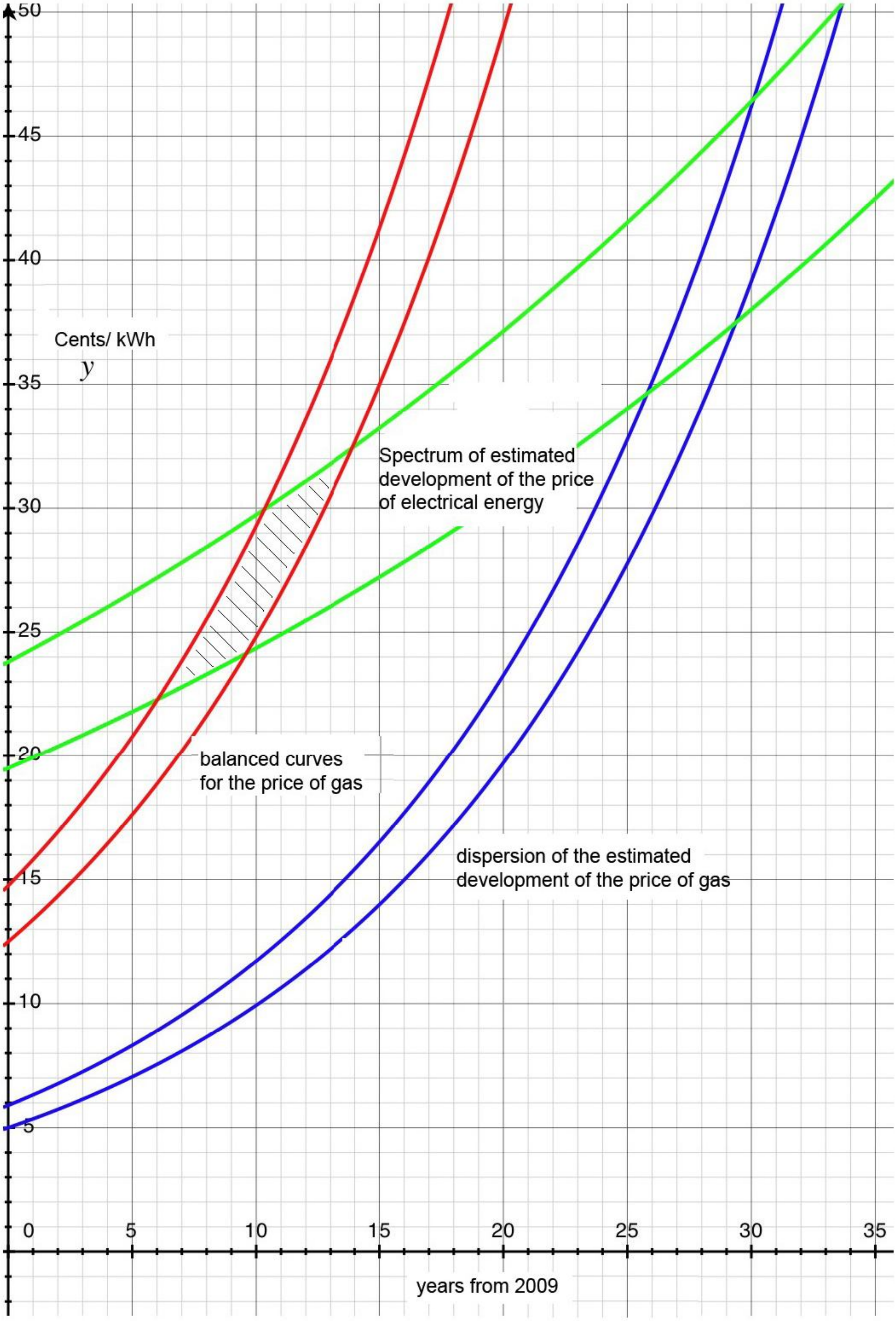
Electricity prices have increased in the last 10 years since the liberalization of the market by approx 2.25% per year; the price of gas by approx 7.1% per year. The relationship between the prices of gas and oil will be maintained in the near future and both fossil fuels will be less available in the future. The increase in the price of electrical energy was 40% caused by state levies, and the first results of cost reductions due to the production of renewable electrical energy have started appearing. The different price development of the two energy forms is thus very likely to change in future, i.e. the price of gas is likely to grow faster than the price of electrical energy.
Assuming this, Pic. 5.1 displays this development with regards to the above-mentioned numbers.
The blue curves show the development of gas prices while the green ones show the development of the prices for electricity, always for a number of years from 2009.
As the gas consumption for gas heating in kWh is at least 2.5 times the consumption of electrical energy for infrared heating, the price of gas has to be balanced out with this coefficient of altered consumption. This is shown by the red curves.

Estimate of the cost alignment between infrared heating and gas heating

Pic. 5.1 shows that the lower balanced curve of the gas price and the top curve of the price of electricity will intersect in approx. 14 years, i.e. at this time, at the latest, the consumption of infrared heating will be more advantageous than the use of gas heating. As the investment costs of infrared heating amount to approximately only half of those for gas heating according to the first rough estimates, the cost advantage will arrive significantly earlier, or even be achieved immediately. The total area of overlap, in which the costs of gas consumption might be higher than the cost of electricity consumption, is marked by hatching on the diagram.

Locally, retailers provide special tariffs for so-called current for direct heating. Thus, the consumption costs of infrared heating are immediately more advantageous than the costs of gas heating.

Even if the real development of the estimated spectrum shown in pic. 5.1 differed, it is still necessary to take into consideration that matters are very likely to develop in a similar manner.



Pic 5.1: Estimated price development – electrical energy versus gas

5.3 Interpretation from the point of view of sustainability/ecology

CO_2 emissions
The average value of CO_2 emissions in Germany was 541 g/kWh (source: BDEW) for the production of electricity in 2007. Newer data hasn't been published yet and therefore this value is used. Because the contribution of renewable energies to combination electrical energy is increasing, the current emission value is probably lower.

When comparing CO_2 emissions, a whole-year combination of electrical energies was intentionally considered, even though the amount of current from coal power plants, and thus the amount of CO_2, is higher in the winter half of the year than in the summer. However, this is also true for the proportion of current from wind power plants, the capacity of which keeps increasing. First of all, a rough point of orientation needs to be found. In order to take account of the momentarily different CO_2 emissions, spatial fluctuations would have to be taken into account alongside time fluctuations. However, such detailed monitoring would take attention away from the trend towards the fastest possible transition to renewable energy sources. Recommendations for fossil fuels due to short-term lower CO_2 emissions would be counterproductive with regards to this trend, as usage was determined for at least 20 years.

The standard value used for heating using gas condensation boiler technology - 249 g/kWh (IWU 2006) – is used as a comparative quantity for gas heating, even though the low-temperature gas heating installed in the measured building was stronger from the emissions point of view. Therefore, an adjusted calculated value of consumption for the gas condensation boiler technology (BWG) was used for the comparison in the measured building. If emissions are balanced out by energy consumption related to the floor space (living area), the data is as follows:

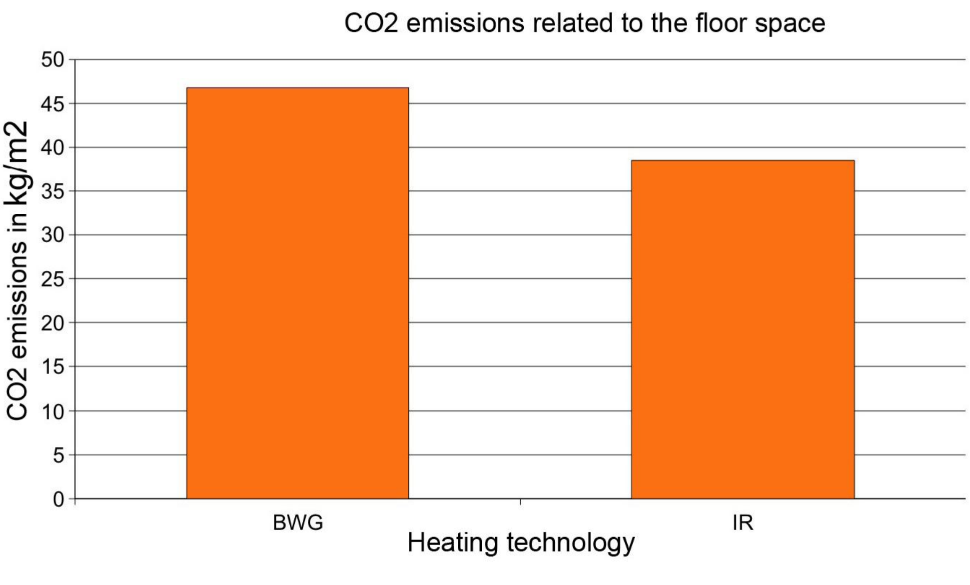
CO_2 emissions of infrared heating (IR) related to the floor space:

541 g/kWh * 71.21 kWh/m^2 = **38.52 kg/m^2.**

CO_2 emissions for heating with a gas condensation boiler related to the floor space:

249 g/kWh * 187.85 kWh/m^2 = **46.77 kg/m^2.**

The values are shown in **pic. 5.2**.



Pic. 5.2: **Comparison of CO_2 emissions**

The difference between both values is sufficiently great, and therefore a general statement can be made that infrared heating – as far as CO_2 emissions are concerned – achieves better results than heating with gas. This is even more true if 100% of the electrical energy used is renewable.

Discussion regarding energy quality

In discussions about the use of electrical energy for heating purposes, the term exergy is used frequently to describe the proportion of that form of energy which can be used to the maximum. The higher the exergy is, the higher the physical quality of the form of energy is. Electrical energy thus has a significantly higher quality than thermal energy. Because of this definition of quality, an oft-presented opinion is that electrical energy “harms” heating.

This evaluation is completely incorrect as far as “sustainability” is concerned. As was stated in detail in the introductory information for the topic “forms of energy and sustainability”, it is mainly important whether the energy comes from renewable resources or not. In this way the ecological quality of the form of energy is created. It is the renewable sources of energy, which are the richest in potential, such as the Sun and the wind, which are especially easy to use for the obtaining of electrical energy. The final energy in the form of electric current from renewable resources thus has to be given the highest priority.

Infrared heating, propelled 100% by electric current produced in a renewable way is one of the most sustainable forms of heating. As in the meanwhile the cost of 100% renewable household electrical energy has reached the price level of conventional forms of heating, there is no economic reason for preferring the standard combination of electrical energies (see above).

5.4 Interpretation from the medical and wellness points of view

Even though no medical or wellness study was explicitly carried out, rather many unsolicited subjective evaluations from inhabitants and visitors were created on this topic.
Their typical statements were:
- no smell from dust/from heating; this property was positively appraised mainly by people who suffer from asthma – these formed a large proportion of the visitors;
-warm feet (in contrast with the previous situation with convection heating);
-fresh (cool) air;
-cosy warmth.

In the measured building there were no urgent problems with mould formation. Even so, it can be generally said that the drying of walls helps against the formation of mould and all of the problems related to this issue.

5.5 Critical remarks regarding the contents of internet pages and advertising statements in the leaflets of producers

Within the period of the project, many interviews with visitors to the measured building took place. Apart from this, many questions were asked about the project, both by specialists and by lay people who were made aware of the project via the project home page. In these interviews and questions, many queries arose regarding the internet pages and leaflets of the producers of heaters. In the next paragraphs we’ll deal with the most frequent mistakes in the advertising statements found in such places.

- Perpetual motion and the great efficiency of radiation

Via the wrong application of equations which concern the physics of radiation, it is often claimed that infrared radiators give off more radiant performance than that which is supplied to them in the form of electrical wattage. The infrared radiator would thus achieve perpetual motion, which contradicts the physical law of conservation of energy. Such statements don’t make sense, and they cannot be taken seriously.

Also, extreme data about the efficiency of radiation is not reliable. Radiators with a filter cannot achieve values which are higher than 90% for technical reasons. Data stating 98% to 100% is related to the efficiency of the transformation of electrical energy to thermal energy in total, i.e. the proportion of infrared radiation and the proportion of convection together, not only that of infrared radiation itself. However, the impression is created that this figure refers to the efficiency of radiation only.

- Infrared heaters which aren't

Some sellers of standard electric heating, such as floor, ceiling or wall heating with built-in heating foils, and electrically powered radiators, have been marketing their products as infrared heating. However, these are convection heating systems with a somewhat increased proportion of radiation compared to standard convection heating. It is very likely that the savings which were achieved in this research project (see above) with real infrared radiators cannot be achieved using these means of heating.

This is similar for electrically powered, freely installable surface heating, the surface temperatures of which do not reach 60°C (typically 30°C to 50°C), or those types in which a strong flow (chimney effect) is created as a result of their structure. Here also the proportion of convection prevails.
This kind of heating is also praised with flowery words as infrared heating, even though it isn't this kind of heating at all according to the above-stated definition.

6 Conclusions and future prospects

The presented research was able to prove that infrared heating is a realistic alternative to common heating systems.

It still isn't taken into consideration in standards (e.g. the efficiency of radiation in electric surface heaters) and regulations (e.g. EnEV), or it isn't given sufficient consideration.
In EnEV, it is presented as being equal to standard electric direct heating, even though marked savings can be expected from it with regards to the principle of heating by radiation as opposed to heating via common electric direct-heating devices, which heat on the basis of convection.

In the above-mentioned company research studies, savings of about 50% are typically stated when comparing electric floor heating or night storage heating to infrared heating. These statements were proven indirectly by the presented project because company comparisons between gas heating and infrared heating were confirmed quite directly.

The replacement of night storage heating and electric floor heating would be, thanks to the easy modification work (little or no additional electrical wiring work needed, only the installation of an infrared radiator) and particularly the low investment costs (typically half or less of that of corresponding heating with a gas condensation boiler), an easily feasible measure for the increase of efficiency.

Other quality criteria which are in favour of infrared heating are:
- low investment costs,
- no side expenditures (e.g. chimney sweeps)
- no need for maintenance,
- 100% renewable operation.

Even though no comparative studies were carried out as far as products are concerned, the general properties of infrared radiators (radiators with a filter) in a residential area can be summarized from the results of this project:
- surface temperatures of 60°C to 120°C,
- no storage mass, and
- surface extensions are as simple as possible in order to minimize the proportion of convection.

During further research, the sample results of the presented study should be based on a wider data foundation. Particularly, the criteria of selection and dimensioning for infrared heating systems should be discovered both for the renovation of existing buildings and also for newly-built homes. The replacement of night storage heating is particularly interesting here.
Apart from this, it is possible to create realistic alternatives for the heating of drinking water which are as sustainable and as efficient as possible compared to standard methods.

7 Index of literature

In the following text, only basic textbooks will be listed as background information. For easier orientation, links to literature are provided directly in the report, in the relevant chapters (in brackets).

Kübler, Thomas: Technology of Heating with Infrared Radiation for Large Areas, Vulkan Verlag 2001

Herwig, Heinz: Heat transfer A – Z: Systematic and Detailed Explanations of Important Quantities and Conceptions, Springer Berlin, 1st edition, 2000

Polifke, Wolfgang; Kopitz, Jan: Heat transfer. Background, Analytical and Numerical Methods Using the SoftwarePaket Scilab on CD-ROM; Pearson Studium 2005

Herr, Horst: Heat Science: Technical Physics 3; Europa-Lehrmittel; 4th edition`, 2006

Konstantin, Panos: A Book on Energy Management: Transformation, Transfer and Acquisition of Energy in a Liberalized Market; Springer Berlin; 2nd edition 2009

Petermann, Jürgen (publisher): Safe Energy in the 21st Century, Hoffmann and Campe, 2008

Appendices

Appendix A: Tables

Table 1: Measured daily electricity consumption values – identification number of heating according to the measurement groups

Date	Group 1 [kWh]	Group 2 [kWh]	Group 3 [kWh]	Group 4 [kWh]
16.11.08	3.257	2.953	26.739	14.517
17.11.08	3.315	3.153	24.995	13.064
18.11.08	5.724	2.953	27.581	17.812
19.11.08	3.824	3.623	28.052	14.595
20.11.08	2.687	2.937	29.465	15.728
21.11.08	2.233	2.834	28.239	16.828
22.11.08	3.369	3.194	24.664	18.079
23.11.08	3.543	3.375	25.364	17.131
24.11.08	2.957	3.520	24.997	17.697
25.11.08	3.842	3.261	26.415	14.635
26.11.08	3.750	3.465	26.348	14.369
27.11.08	3.885	3.544	26.546	13.572
28.11.08	3.975	3.648	26.901	14.598
29.11.08	4.199	3.757	26.448	13.738
30.11.08	3.967	5.202	25.856	8.896
01.12.08	4.636	2.990	26.293	14.686
02.12.08	3.949	3.502	25.245	16.293
03.12.08	3.719	3.465	28.555	14.503
04.12.08	3.907	3.204	23.987	11.793
05.12.08	3.354	3.120	25.323	10.242
06.12.08	2.664	3.199	18.922	12.618
07.12.08	2.775	2.996	22.896	12.983
08.12.08	3.419	3.238	25.765	14.439
09.12.08	3.976	3.476	26.298	14.675
10.12.08	3.968	3.681	25.748	14.480
11.12.08	4.103	3.558	26.260	14.363
12.12.08	4.336	3.479	26.707	14.752
13.12.08	4.609	3.723	27.223	15.136
14.12.08	5.218	4.193	28.501	14.713
15.12.08	5.015	3.759	26.927	15.165
16.12.08	3.941	3.791	26.914	15.092
17.12.08	4.740	3.709	27.309	14.795
18.12.08	4.463	3.761	26.870	14.788

19.12.08	4.031	3.630	26.618	14.694
20.12.08	3.855	3.615	25.165	13.680
21.12.08	2.291	3.251	23.854	10.399
22.12.08	2.340	2.707	23.950	8.533
23.12.08	2.110	2.628	24.445	9.465
24.12.08	2.611	3.134	25.748	13.507
25.12.08	3.716	3.238	25.415	14.370
26.12.08	3.886	3.260	26.679	14.820
27.12.08	5.044	4.560	27.586	15.593
28.12.08	4.760	4.351	27.773	16.391
29.12.08	5.722	4.748	28.633	16.421
30.12.08	5.643	4.837	28.976	17.438
31.12.08	5.892	3.835	27.954	19.099
01.01.09	5.173	2.612	26.402	18.545
02.01.09	5.724	2.852	27.263	17.806
03.01.09	5.071	3.769	31.755	21.423
04.01.09	6.304	4.233	30.499	22.104
05.01.09	5.882	4.016	29.528	19.537
06.01.09	5.936	4.036	30.918	22.210
07.01.09	7.344	3.770	30.765	24.626
08.01.09	7.023	3.933	31.659	30.812
09.01.09	7.655	3.643	33.737	32.188
10.01.09	7.362	3.268	33.983	29.199
11.01.09	8.136	3.359	32.511	32.990
12.01.09	7.562	3.453	32.379	33.142
13.01.09	6.148	3.519	32.154	31.586
14.01.09	5.450	3.689	28.003	26.967
15.01.09	5.571	3.749	28.112	32.583
16.01.09	5.744	2.933	27.107	18.532
17.01.09	5.622	4.112	28.329	17.541
18.01.09	3.299	3.240	24.440	16.852
19.01.09	3.645	4.419	23.062	20.770
20.01.09	3.310	4.070	24.458	20.234
21.01.09	3.973	3.911	18.963	17.031
22.01.09	4.432	3.952	27.609	23.820
23.01.09	3.813	3.871	23.546	14.870
24.01.09	3.567	4.413	23.461	9.166
25.01.09	1.823	5.856	24.489	13.040
26.01.09	4.529	3.765	28.138	2.297
27.01.09	5.185	3.818	30.266	14.056

28.01.09	5.014	3.667	28.195	11.254
29.01.09	4.645	3.589	28.635	12.546
30.01.09	5.084	3.570	29.308	13.144
31.01.09	5.553	3.966	31.194	19.531
01.02.09	4.930	4.721	28.633	27.281
02.02.09	4.607	4.404	28.691	26.619
03.02.09	1.224	6.303	26.122	18.594
04.02.09	4.791	4.255	21.824	25.427
05.02.09	3.430	3.448	21.013	19.808
06.02.09	3.782	4.522	29.739	21.493
07.02.09	3.396	3.472	21.479	20.036
08.02.09	3.848	4.458	29.194	21.354
09.02.09	4.229	3.699	28.536	23.153
10.02.09	4.278	3.577	26.842	19.947
11.02.09	4.009	3.947	24.553	16.496
12.02.09	3.907	4.251	29.557	22.971
13.02.09	4.722	3.996	27.953	24.881
14.02.09	4.391	3.350	25.838	19.825
15.02.09	4.889	4.982	27.507	26.652
16.02.09	4.781	4.084	28.306	24.415
17.02.09	4.168	4.286	27.003	22.272
18.02.09	4.393	3.702	27.832	22.926
19.02.09	5.065	4.584	29.100	24.810
20.02.09	4.766	3.951	28.746	23.244
21.02.09	3.782	4.584	29.031	21.172
22.02.09	3.871	4.496	24.213	15.884
23.02.09	3.591	3.715	27.230	20.091
24.02.09	3.356	4.281	25.220	19.151
25.02.09	3.716	4.087	25.905	18.361
26.02.09	3.738	3.962	24.267	19.888
27.02.09	3.540	3.998	19.185	19.160
28.02.09	2.894	3.995	17.952	16.868
01.03.09	3.090	4.096	17.229	16.700
02.03.09	2.050	3.907	16.260	15.014
03.03.09	2.358	4.185	17.847	17.972
04.03.09	2.957	4.263	18.720	16.841
05.03.09	2.867	4.062	19.257	18.774
06.03.09	3.258	3.831	18.943	21.765
07.03.09	3.570	4.930	17.441	17.737
08.03.09	3.279	3.974	18.832	19.031

09.03.09	2.951	3.815	18.573	18.240
10.03.09	3.435	4.154	17.554	19.585
11.03.09	2.991	3.325	19.751	17.929
12.03.09	3.456	3.855	18.147	20.075
13.03.09	2.984	3.895	17.417	16.260
14.03.09	2.166	3.924	17.529	13.583
15.03.09	1.842	3.576	13.657	15.652
16.03.09	1.943	3.602	14.878	15.071
17.03.09	2.238	3.700	15.465	13.715
18.03.09	2.178	5.250	16.167	13.959
19.03.09	2.880	4.819	19.433	14.531
20.03.09	2.314	4.991	21.673	15.157
21.03.09	3.574	5.387	25.056	14.318
22.03.09	3.920	5.482	20.987	21.867
23.03.09	2.814	4.418	19.357	18.095
24.03.09	3.166	3.606	20.257	19.235
25.03.09	3.539	4.714	21.300	22.963
26.03.09	3.823	4.104	18.433	21.561
27.03.09	3.481	3.862	21.665	18.040
28.03.09	2.709	4.405	19.428	16.872
29.03.09	2.571	3.750	13.665	17.649
30.03.09	2.103	4.942	14.862	14.692
31.03.09	0.846	1.601	8.069	8.177
01.04.09	0.649	1.935	5.934	7.328
02.04.09	0.491	1.284	3.871	5.274
03.04.09	0.538	1.474	4.277	0.117
04.04.09	0.416	1.327	3.475	0.225
05.04.09	0.387	1.225	2.884	0.093
06.04.09	0.279	1.359	2.993	0.051
07.04.09	0.361	1.184	3.714	0.025
08.04.09	0.355	1.411	3.922	0.018
09.04.09	0.478	1.672	3.543	0.015
10.04.09	0.642	1.992	3.454	0.016
11.04.09	0.222	1.482	3.369	0.012
12.04.09	0.797	1.773	3.233	0.018
13.04.09	0.827	1.338	2.980	0.015
14.04.09	0.616	1.944	3.009	0.018
15.04.09	0.472	1.829	2.352	0.018
16.04.09	0.416	1.369	7.621	6.589

17.04.09	1.000	2.073	15.782	11.536
18.04.09	1.449	3.116	16.361	12.410
19.04.09	0.552	1.982	13.189	4.954
20.04.09	0.248	1.657	8.172	2.887
21.04.09	0.024	1.135	9.271	2.478
22.04.09	0.030	1.086	8.201	4.318
23.04.09	1.123	2.564	10.630	8.778
24.04.09	1.803	2.706	12.957	7.309
25.04.09	1.507	2.158	15.070	7.377
26.04.09	0.530	1.066	10.792	5.457
27.04.09	0.220	1.125	6.825	6.334
28.04.09	1.135	1.972	12.020	9.188
29.04.09	1.537	2.501	11.367	9.939
30.04.09	0.864	2.313	14.122	10.055

Table 2: **Measured weekly electricity consumption values – identification number of heating according to the measurement groups**

Calendar weeks 2008/09	Weekly values Group 1 [kWh]	Weekly values Group 2 [kWh]	Weekly values Group 3 [kWh]	Weekly values Group 4 [kWh]
47	27.95	25.02	215.1	127.75
48	26.58	26.4	183.51	97.51
49	25	22.48	171.22	93.12
50	29.63	25.35	186.5	102.56
51	28.34	25.52	183.66	98.61
52	24.47	23.88	181.6	92.68
1	39.53	23.88	201.48	132.84
2	49.34	26.03	223.1	191.56
3	39.4	24.7	200.52	177.2
4	24.56	30.49	165.59	118.93
5	34.94	27.1	204.37	100.11
6	25.08	30.86	178.06	153.33
7	30.43	27.8	190.79	153.93
8	30.83	29.69	194.23	154.72
9	23.93	28.13	156.99	130.22
10	20.34	29.15	127.3	127.13
11	19.83	29.15	122.63	121.32
12	19.05	33.23	133.66	108.62
13	22.1	28.86	134.11	134.42
14	5.43	13.79	43.37	35.91
15	3.13	10.87	24.23	0.16
16	5.33	13.65	61.29	35.54
17	5.27	12.37	75.09	38.6

Table 3: Measured weekly values – flow consumption for gas heating

Weekly gas consumption

Date	**State of the measuring device - gas**	**Calendar weeks 2008/09**	**Weekly gas consumption – cubic metres**	**Weekly gas consumption - kWh**
16.11.08	61766			
23.11.08	61901	**47**	135	1408.05
30.11.08	62075	**48**	174	1814.82
07.12.08	62233	**49**	158	1647.94
14.12.08	62404	**50**	171	1783.53
21.12.08	62568	**51**	164	1710.52
28.12.08	62720	**52**	152	1585.36
04.01.09	62925	**1**	205	2138.15
11.01.09	63153	**2**	228	2378.04
18.01.09	63357	**3**	204	2127.72
25.01.09	63525	**4**	168	1752.24
01.02.09	63713	**5**	188	1960.84
08.02.09	63882	**6**	169	1762.67
15.02.09	64052	**7**	170	1773.1
22.02.09	64220	**8**	168	1752.24
01.03.09	64359	**9**	139	1449.77
08.03.09	64489	**10**	130	1355.9
15.03.09	64611	**11**	122	1272.46
22.03.09	64734	**12**	123	1282.89
29.03.09	64826	**13**	92	959.56
05.04.09	64929	**14**	103	1074.29
12.04.09	64959	**15**	30	312.9
19.04.09	65017	**16**	58	604.94
26.04.09	65064	**17**	47	490.21
30.04.09	65097		33	344.19

Pic. B1: Bathroom

Pic. B2: Kitchen