EFFICIENCIES OF DOMESTIC HOT WATER PRODUCTION

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Abstract: Due to a strict governmental policy on energy performance for new domestic buildings and the inherent better insulation and parallel the higher comfort demands for domestic hot water (DHW) by the end use, the energy use for DHW is becoming dominant in the overall energy use of the house.
The combination of space heating and DHW in one heat generator like a high efficiency condensing gas boiler for which the capacity is chosen on the instantaneous demand for high comfort DHW (being 32kW), is no longer the obvious solution as the peak demand for space heating decreases to 4kW and lower. Low capacity systems combined with water storage tanks for DHW get more interesting.
In a study done by the authors for the Netherlands Enterprise Agency (RVO) eleven individual concepts and eight collective systems providing domestic hot water have been compared on the aspect of system losses and primary energy use in the complete chain from the generation system to the individual end user down to the level of kitchen and bath room. Systems are both based on fossil fuels and renewables. The results show best case efficiencies of each system where heat pumps as well as solar thermal systems have the highest performances, under certain boundary conditions, on system efficiency. Further recommendations are made to increase the efficiency.

Key Words: heat pumps, efficiency of domestic hot water, individual and collective systems

1 INTRODUCTION

For several decades in the Netherlands there is a decreasing heat demand for space heating in the domestic housing market as a result of Dutch policy on energy conservation. Newly built houses have to meet a better Energy Performance Standard (EPC) where the bar has been raised every couple of years with the goal to get to Nearly Zero Energy Buildings by 2020. Coming from an EPC=1.0 this has to be EPC=0.4 in 2015 for new buildings to get an official building permit. The peak capacity for space heating at –15°C outside temperature, decreases in new domestic buildings to 4kW with a base capacity in mid-season of only 1kW.
The large market of renovation of existing buildings is supported from government by information and subsidy schemes. The energy performance of the building is rated according to a label scheme which is not yet mandatory. In practice upgrading focuses mainly on insulation and double glazing for private ownership reducing the peak demand in terraced houses to 8 – 10kW and base demand to 2 – 4kW. In large renovation projects in the collective sector the upgrading of building complexes undertake, next to insulation, the renovation of heating distribution systems and heat generators [Ref 5]. In an agreement with

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the government, the association of housing corporations have agreed upon a program to increase the energy performance with a minimum of two label steps.

At the same time, there is a trend with the end user towards a greater comfort of hot water (drench showers, luxurious baths, etc.). The basic tapping patterns (frequencies and volumes of DHW use throughout the day) are in the Dutch standard classified by class 1 – 6, where class 6 denominates the highest comfort and tapping volumes. A large part of the market sales of high efficiency gas boilers is in class 4 – 6. The capacity of the heat generator is then chosen, if there is no DHW storage system is installed, on the instantaneous demand being 32kW for a class 6 tapping pattern. The combination of these trends with a lower demand of space heating and an increasing capacity demand for DHW is shown in Figure 1.

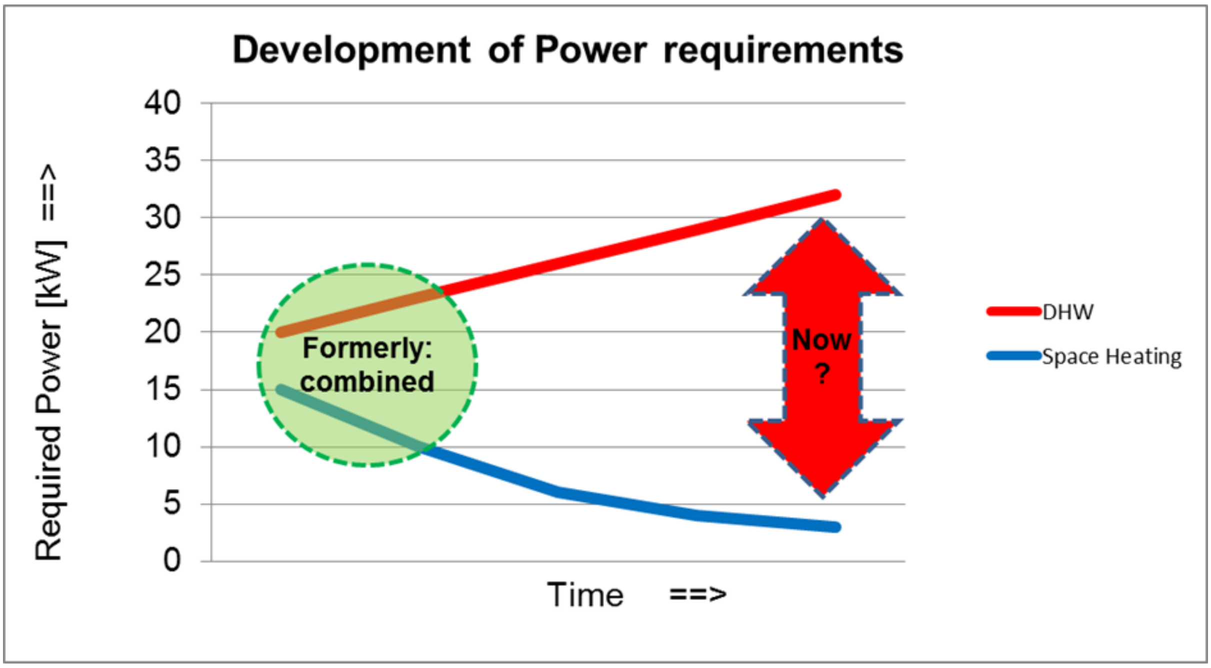

Figure 1: Trends in direct capacity demands of DHW and space heating

The combination of space heating and domestic hot water in one heat generator like a high efficiency gas boiler is no longer the obvious solution as this combination has a large impact on the overall efficiency of the system. The study shows that the same goes for other heating systems as well and that it is very important to focus the design of a heating system on the energy efficiency of the production of domestic hot water. While the end user may only be interested in the efficiency of the apparatus, for energy policy the overall efficiencies for the complete chain from primary (fossil) energy to the end user have to be compared; the benefits of a highly efficient generation device can be nullified by a poor system integration and large storage or distribution losses.

The overall efficiency of domestic hot water (DHW) is influenced by several aspects inside and outside the dwellings. Main aspects are:

- The efficiency of the heat generator for DHW and the loss in efficiency for space heating if both are combined in one generator.
- The position of the heat generator and its distance to the hot water taps in the kitchen and the bathroom in the building, resulting in ‘in house’ distribution losses.
- The behavior of the consumers and demand patterns resulting in the tapping of many short and small amounts of hot water in the kitchen and large amounts in the bathroom.

- Temperature level needed through legislation to prevent legionella growth in the system.
- Transport and distribution losses through heat losses and distribution pump energy in district heating systems and in collective systems for multifamily buildings.
- The real efficiency of electrical power generation and the development over the life cycle of the generator or the overall system. At this moment the efficiency is fixed in the standard not taken into account the co-firing of bio-fuels.
- Type of fuel and heat generating efficiency in collective systems, ranging from gas or coal in a power station or local cogeneration to waste incineration and bio fuels.

In the end the Netherlands Enterprise Agency thinks it is of importance that all the factors have to be taken into account to be able to choose for a robust and reliable system for the next decades.

2 CONCEPTS PROVIDING DOMESTIC HOT WATER

In the Netherlands many different system configurations have been applied or are under development as new alternatives. In this study several of the most prominent systems were analyzed, split in individual systems per house and collective systems on multifamily houses or for districts and towns.

Individual systems:
The reference is the High efficiency condensing gas boiler providing instantaneous DHW (no storage) and space heating (SH), being the Dutch standard for heating systems in domestic houses. Other systems in the comparison are:

- Combined systems that provide DHW as well as SH:
  - Heat pump storage water heater by a gas fired diffusion absorption heat pump, with BTES as heat pump source
  - Hybrid outside air source heat pump with high efficiency gas boiler for peak load in space heating and instantaneous DHW without storage.
  - Heat pump storage water heater, with outside air as heat pump source;
  - Heat pump storage water heater, with BTES as heat pump source;
- Separate systems which only provide DHW:
  - Gas fired storage water heater
  - Storage heater on a high efficiency gas boiler
  - Electric storage water heaters, a small one in the kitchen and a large one for the bathroom.
  - Electric instant flow heaters, two separate devices for bathroom and kitchen
  - Solar storage water heater with high efficiency gas boiler (water tank is on available solar energy temperature, if necessary, water is reheated to the right temperature in a separate HX just before use)
  - Heat pump storage water heater on ventilation exhaust air as source;

Collective systems:
More than 50% of the multifamily buildings and apartment blocks in Netherlands are heated by one central heating system distribution the heat for space heating and DHW to the individual end user. District heating systems can be found in larger cities like Amsterdam, Rotterdam, The Hague and Utrecht. Also smaller systems are under consideration with a lot of political interest for industrial excess heat. On the other hand large energy companies are withdrawing from this market as the decreasing heat demand makes the economic perspective rather meagre. Systems discussed in the comparison are:

- Gas fired central heating boiler for space heating and DHW in a multifamily apartment building.

- Collective solar storage water heater in multifamily building with gas fired auxiliary back up heating
- Ground source (BTES) gas fired absorption heat pump in a multifamily apartment building.
- Open ground source (ATES) electric heat pump with heat distribution to the individual domestic (terraced) houses at 70°C supply and 40°C return (“mini” district heating).
- District heating with central heat generation by gas fired boilers.
- District heating on a gas fired electricity generating steam cycle by means of a gas- and steam turbine combination (CHP); electrical efficiency decreases caused by heat extraction on steam cycle.
- District heating based on incineration rejected heat of electricity generating steam cycle; electrical efficiency decreases caused by heat extraction on steam cycle
- Hybrid system [Ref. 1] based upon a low temperature district heating (45°C supply and 30°C return) and a small heat pump with DHW storage tank in each dwelling (Figure 2).

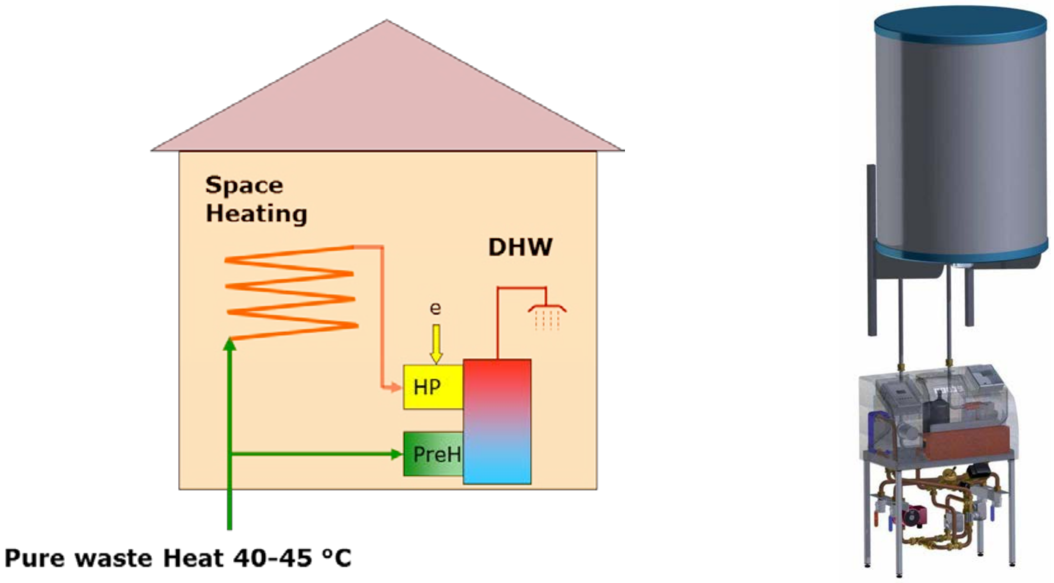

Figure 2: Schematic Diagram of the Hybrid System (Infinitus) and example of a Booster Heat Pump (Ecoon) with water storage

In collective heat distribution systems the long distance of heat transport and distribution to the individual end user and the losses have to be taken into account. The average value of transport and distribution losses for these large district heating systems is based on 70°C supply and 40°C return, although practical temperatures are often much higher. In applying district heating often the argument of high heat demand density in areas with multifamily apartment buildings is used as a benefit for these systems. However the losses inside the building have to be taken into the calculation when compared to individual systems. Another discussion is on the economy of energy conservation measures where in the Dutch energy standard it is ‘allowed’ to have less insulation on the envelope of the building if the central heat generator is efficient. This new standard (NVN 7125) is under development.

3 EFFICIENCIES OF DHW-SYSTEMS

In this study the comparison of systems is based upon the chain efficiency where the overall efficiencies for the complete chain from primary (fossil) energy to the end user are compared and the weakest links in the chain are analyzed. All options have been modelled and calculated in order to be able to analyze the efficiency of the different DHW-options, The following aspects were taken into account:

- Basic efficiency of the conversion from primary energy (natural gas or electricity) into heat
- Energy losses during starting and stopping of the heat production
- Energy losses of the water storage tank
- Transport and distribution losses (collective systems)
- Energy use of auxiliary/utility equipment (fans and pumps)
- Energy for prevention against legionnaires disease: weekly heating of DHW storage tanks from 55 to 65 °C
- Auxiliary heating (solar system and collective systems)

In the modelling a central production efficiency of electricity of 47% (based on lower heating value) was used, this being the average value in 2009 in the Netherlands [Ref. 2]. As this figure is excluding combined heat and power and renewables the overall efficiency is in effect higher.
Heat pump COP's were based on test results at TNO (Netherlands Organisation for Applied Scientific Research). The tests were performed with a net demand of DHW of 14 GJ per year, where this study is based on a net demand of 9 GJ per year. Test values were adjusted and resulted in a lower COP for this study because the energy losses of the storage tanks become relatively higher compared to the actual use.
Efficiencies of gas fired equipment were based on discussions with KIWA/Gastec (Dutch institute for certified testing of gas fired equipment).

The aspects mentioned above were taken into account to assess the system efficiency of the DHW-production. Figure 3 shows the overview of all calculated aspects.

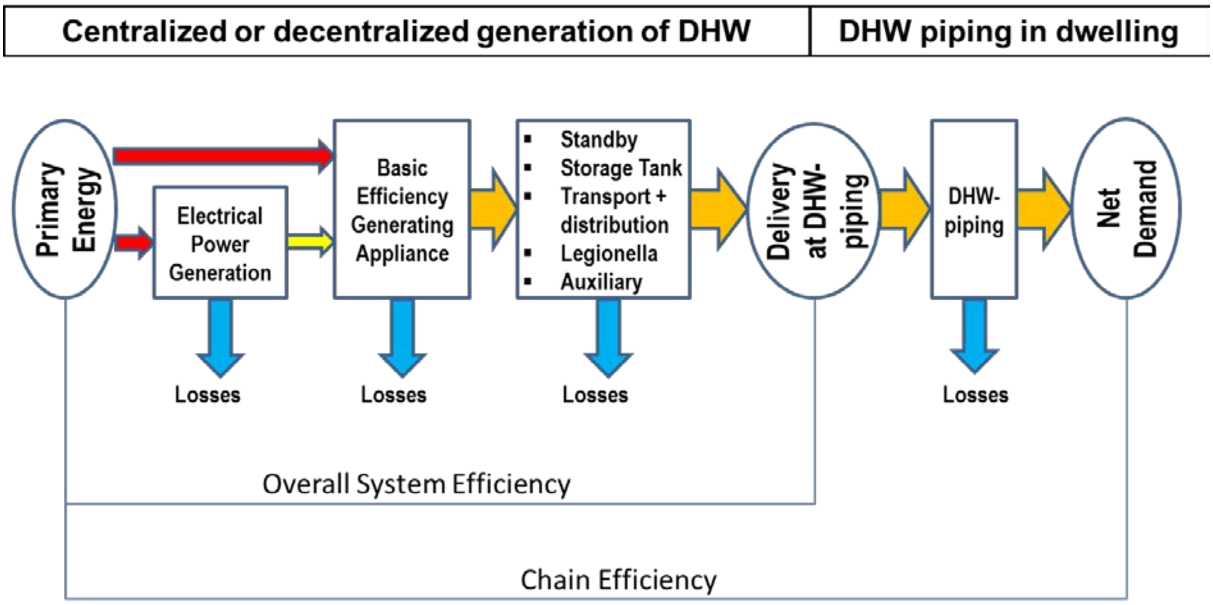

Figure 3: Definition of efficiencies

In the first stage the conversion efficiencies of the apparatus are compared. In Europe the Eco-Design of Energy-Related Products for efficiency of water heaters (Lot 2) [Ref. 3] will become the benchmark standard from 2015 onwards. For the heat pumps the energy losses of the water storage tank are included. Heat pumps, perform good in this comparison because they use renewable sources. Rejected heat from electricity production with combined heat and power with steam and gas turbines or the steam cycle of a waste

incinerator power station also results in high calculated values of efficiency. However these values are based upon a hypothetical efficiency of heat generation, which is highly dependent on the basic assumptions regarding the reduced electricity production and the quantity of traditional (gas fired) auxiliary heating [Ref. 4]. In the comparison the results of a best case approach for all systems are given.
The hybrid district heating with booster heat pump storage heater achieves the highest efficiency because the DHW is preheated with very low temperature waste heat and then reheated with the micro heat pump (all values are related to a net DHW-consumption of 9GJ/year).

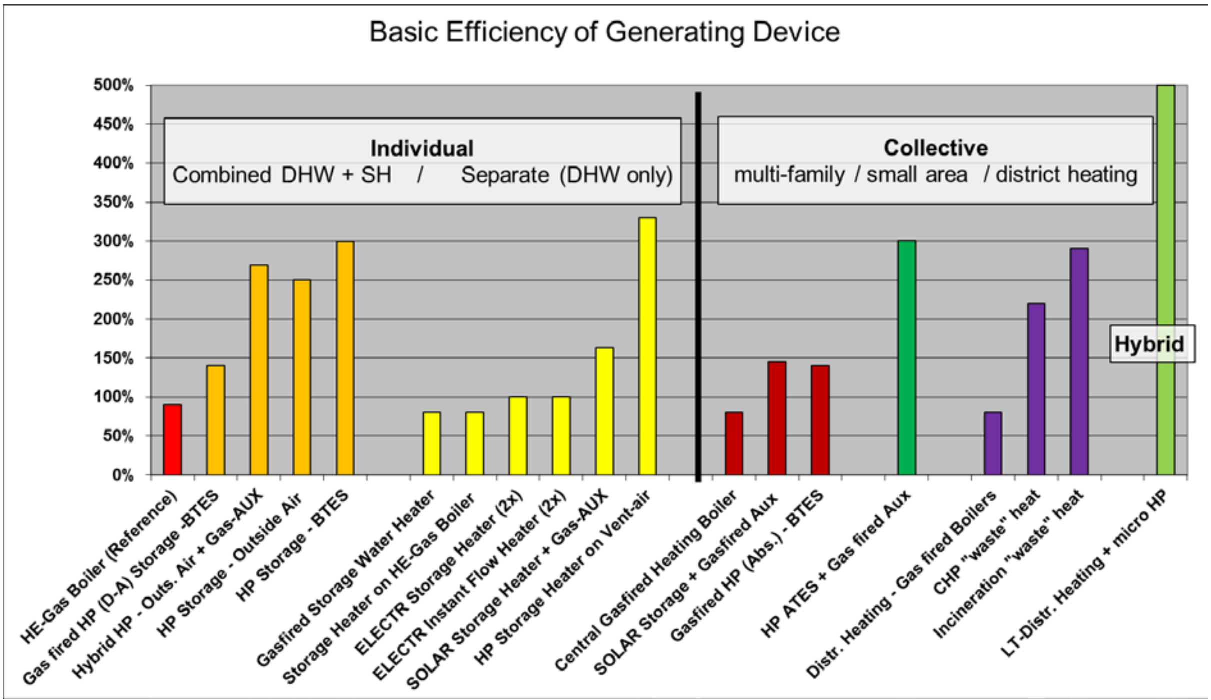

Figure 4: Basic generation efficiencies at a demand of DHW of 9 GJ/year

In combined and separate concepts the main energy loss is caused by the water storage tank. In collective concepts is the largest energy loss is in the transport and distribution of the heat (DHW is produced inside the dwelling with a plate heat exchanger). Only a part of the distribution system between the location of the heat production and the dwellings is allocated to DHW production. These are the losses outside the heating season to keep the network up to temperature and the additional losses during the heating season because the use of an outside temperature-dependent supply temperature is not possible[3].

There are a number of standard available heat pump water heaters developed by Dutch manufacturers with special attention to minimizing the downtime losses of the storage tank by optimizing the insulation of the water storage tank, highly stratified tapping curves, pipe connections and a smart control. This results in average heat losses lower than 40W and COP's as high as 4.0. In such cases the volume of the storage can be as small as 150 liters giving sufficient DHW during the day. Solar water heaters from the same manufacturers have a high efficiency because the high efficiency gas boiler is outside the storage tank giving instantaneous back up when tapping. The storage tank is thus only used for storing solar thermal energy which can be at a lower temperature than needed at the tap.

An overview of main energy losses per concept is shown in Figure 5.

[3] *All losses are related to a net demand of DHW of 9 GJ/year.*

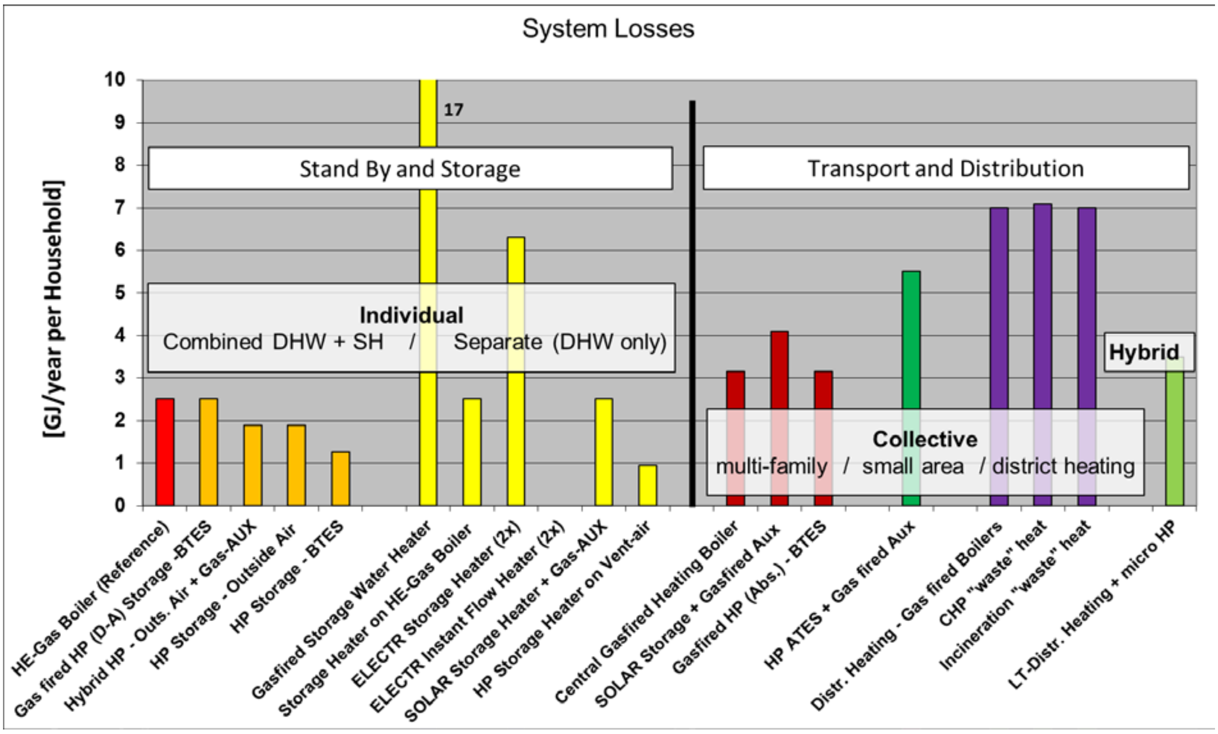

Figure 5: Stand By and Distribution Losses (excluding start/stop losses)

The overall system efficiency of DHW production is given in Figure 6. These values include all aspects of the production from primary energy to the beginning of the DHW piping in the dwellings. The efficiency of electrical power generation is also included.

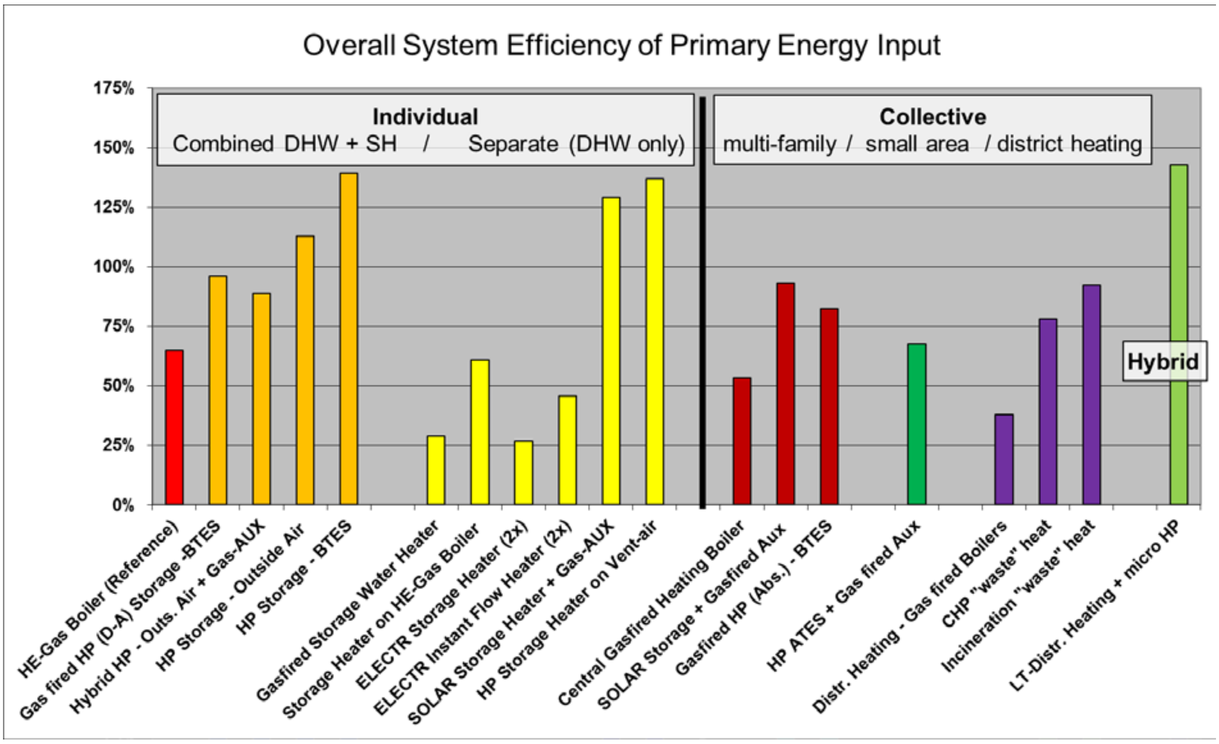

Figure 6: Overall System Efficiency

These results show that:

- Within the separate concepts, the heat pump water heater and solar water heater with gas fired backup result in significantly higher efficiencies than the other systems; within the combined concepts, heat pumps achieve the highest results;
- Within the district heating concepts the residual heat from a waste incineration (AVI) has the highest efficiency
- The hybrid concept gives the best efficiency of all systems, this is mainly due to the preheating of the water using waste heat.

The high efficiencies of heat pumps, solar water heaters and AVI waste heat are, of course, all due to the share of renewable and / or ambient energy that is used in these concepts.

3.2 Conclusion on system efficiency

When the overall system efficiency is compared, hot water production with heat pumps is possible with an efficiency that can be double the efficiency of gas fired boilers. Compared to standard collective solutions, heat pumps also give twice as high efficiencies. Heat pump concepts are even four to five times higher compared to electric resistance heating. The best collective concepts can at the best case have an efficiency comparable to the individual gas fired boilers.

3.3 Chain Efficiency

In the chain efficiency an extra aspect is added: the energy losses of the hot water piping from the apparatus that produces DHW to the hot water taps. Here a best case / worst case approach is used. It is assumed that a hot water pipe contains no usable hot water anymore when the next tapping takes place. Figure 7 shows the assumptions used for the length and diameter of the tapping lines.

For the separate concepts, the piping length within the dwellings is determined based on two locations: placement of the heater for the bathroom in the attic and for the kitchen into the kitchen or above the sink. For the combination concepts and the hybrid heating network placement of the heat generator in the attic is assumed (see Figure 7).

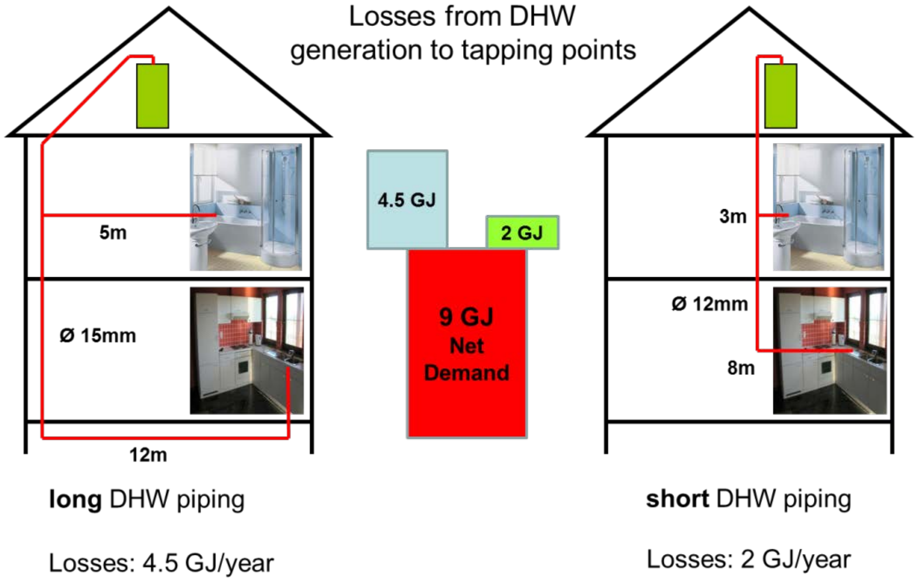

Figure 7: Losses of hot water piping inside the dwellings

For collective concepts the delivery point of the heat, and placement of the heat exchanger, is projected near the front door. This results a short tapping line to the kitchen. The energy

loss of the piping in the dwelling is considered as an additional water demand (not as usable DHW), produced with the basic efficiency of the generating apparatus or system without additional losses of storage tanks or distribution systems.
Figure 7 shows the results of these calculations. The difference between worst case and best case is an energy loss of 2.5GJ/year and varies between 20% and 50% of the net demand of DHW. The extra energy loss of 2.5GJ can be avoided just by a well-engineered design of the hot water piping.
For the combined concepts, where the generation apparatus of DHW is placed in the attic, 80 to 90% of these losses are related to short and frequent use of DHW in the kitchen.
In case of a long distance between the kitchen and the generation apparatus, it is preferable to use a small separate DHW-generator for the kitchen.

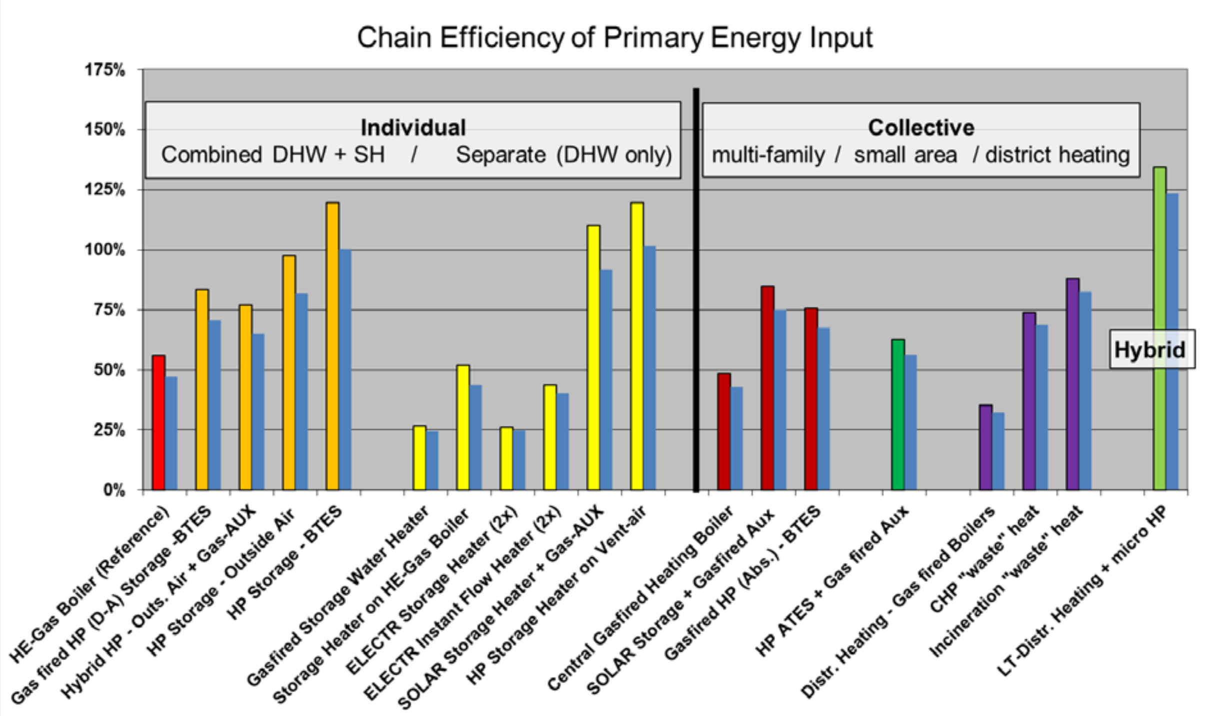

Figure 8: Chain Efficiency

Figure 8 shows the chain efficiency, this is the integration of the inside piping losses and the overall system efficiency for the best case and the worst case (blue columns) approach.
The results above show the difference in efficiency for the different concepts. Application of green energy carriers (or generation) adds an extra dimension, but is disregarded for the purposes of this investigation. Use of biofuels, biogas or geothermal energy for heat generation results in lower CO_2 emissions, as well as the use of wind and solar energy for electricity for the benefit of electric heat pumps. Each concept can basically be fed with green energy and then achieves a higher environmental score.

4 HIGHLIGHTS

A number of guidelines for designing and engineering an apparatus and an optimal DHW heating system can be drawn from this analysis. It is important to think in terms of complete system concepts. Even if the heat is produced with a high energy efficiency, high storage and / or distribution losses still remain unnecessary and eventually will cause a low overall system efficiency to the best generating apparatus. It is therefore important to consider the heat generators not only individually but to design a complete DHW concept with a critical view on performance, comfort and legionella prevention.

Choose generating devices with a high efficiency. A hot water unit with high efficiency (for example, a heat pump storage water heater or solar storage water heater) consumes less primary energy than a device with a low efficiency (for example, a gas fired storage water heater). A hybrid outside air source heat pump with high efficiency gas boiler for peak load in space heating and instantaneous DHW without storage, although not having the best available efficiency, is a very good option in renovation situations.

Install the generating apparatus or water storage tank as close to the tap with numerous small amounts of water use. In the kitchen, where a lot of small amounts of water are used during the day, the impact of the length of the water piping there is the greatest. Compared with generator located in the attic (and a kitchen on the ground floor) approximately 3.5GJ (net) may be saved (at 9GJ net DHW requirement). For newly built houses with a low demand for space heating it is the challenge for the architect and building constructor to realize this option. All newly built homes are designed from the drawing board. It is sensible to take into account the distance between the source(s) of hot water and the taps at this stage already. This allows the user of the house the saving of a lot of energy (and cost) during the operating life of the house.

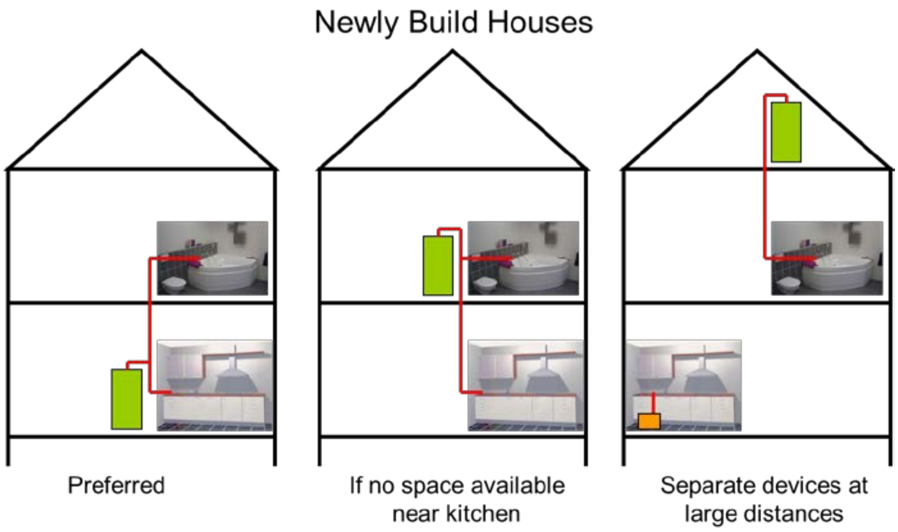

Figure 9: Options for newly build houses

Choose a (device with a) very well insulated storage tank. Do not compromise on the insulation of the water storage tank not only in thickness but also in design where pipe connections at the side or top of the storage tank should be avoided as much as possible. In addition, a smart control depending on the tapping patterns and volumes (lowering the storage temperature during night and / or certain daytimes) reduces the standby losses, without decreasing the comfort level.

Limit unnecessary consumption of auxiliary energy. Auxiliary power is usually only needed during heat production. Choose a control system or adjust set points in such a way that pumps, fans and other auxiliary equipment is not continuous and / or unnecessary in operation.

Insulate hot water pipes optimally. The moment outlet pipes and connections are well insulated, line losses are reduced and the overall efficiency benefits. Potable water pipes have a lifespan of about 50 years. Insulation of the pipes afterwards, in existing situations, often cost a lot of money and time. For this reason, it is wise to install well-insulated pipes right away in difficult to reach spaces and ducts in new houses.

Allocate space for the location of a water storage tank. Several devices that generate hot water have a storage tank in order to have a small capacity generator designed on the need for space heating. Examples include solar water heater, electric water heater, combined heat pump and the heat pump water heater. When the location of a storage vessel is allocated in the design phase, later discussion regarding the placement is prevented.

Separate unit for the kitchen at large distances. In existing domestic housing the heat generator is far from the kitchen. When many small amounts of water are used there throughout the day, the hot water must often travel long distances to the kitchen. This is accompanied by unnecessary waiting, wasting water and lots of energetic line losses. A solution to this is to place a separate DHW heater in the kitchen, for example, by placing an small electric storage water heater (see figure 9 and 10). This immediately raises the discussion that the Eco-design of Energy-Related Products for efficiency of water heaters (Lot 2) [Ref. 3] which labels electric storage water heaters in the category E is the right standard for this case. It moreover proves the statement made that it is important think in terms of complete system concepts rather than to look at the apparatus only!

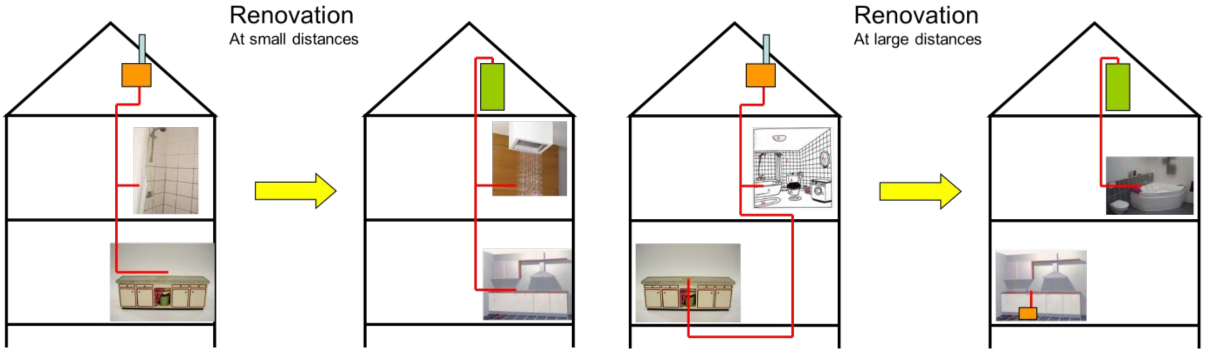

Figure 10: Renovation option in situation of small and large distances (=> separate appliances) between bathroom and kitchen

Combine collective heat supply with individual generation of DHW. Hot water (or the heat therefor) is to be moved over a distance as short as possible. Collective heat supply and district heating for space heating often, however, is combined with the heating for DHW. This results in large distribution and line losses up to 50% (particularly in the transport and distribution pipelines that must be kept at DHW temperatures in the summer) and leads to a low overall system efficiency. Often it is argumented that collective heating systems are of interest for multifamily buildings and apartment blocks having a high and concentrated heat demand at one delivery point, making it an interesting economic solution. However after the collective heat exchanger point the distribution losses inside the building are enormous for which in the end the customer has to pay using actually twice the amount of GJ's for DHW as he would have in an optimal solution.
A solution to this problem is the concept of the hybrid system: distribution of heat with the lowest temperature possible (with the lower losses that accompany it) and production of DHW with the required high temperature in the individual dwellings or apartments [Ref. 1].

5 CONCLUSIONS

The overall energy use for DHW can be improved by improving the devices and apparatus generating the DHW and by a smart design of the in house system. The knowledge of the possibilities are not widely known and applied.

Technological developments with heat pumps almost always are looking into the heat pump technology itself. Although we think that is of importance, we also think that the overall efficiency can be increased firstly by choosing a sustainable generating system (solar water heater, heat pump water heater), and secondly by selecting an optimal combination with the storage water tank and its control strategy. Available water storage tanks differ very much in energy loss (from 50 to 200W). These standby losses, frequency of water use, the placement of the piping on the storage and control strategy of heating greatly affect the performance, not only for heat pumps, but also for other heating systems.

For the design and overall efficiency of the systems the main focal point is the length of distribution from generator to the final tapping point. In house losses in single family houses can be reduced by shorter piping and in multifamily apartment blocks by getting away from collectively generated DHW. We expect that a lot can be gained in existing buildings in renovation by low temperature distribution and individual booster heat pumps [Ref.1].

Important in this study is the observation that collective DHW options like in district heating systems, the distribution system year round (8760 hours) must be kept at the high temperature for the purpose of delivering DHW while for space heating these high temperatures only for a short period during the peak of the heating season are needed. Also important to notice is that the heating season for new homes and after-insulated existing homes has become shorter because of the higher degree of insulation.

On national and international level there is a lot of work to be done which in line with the momentary IEA work is not yet clearly defined in running Annexes. The authors propose to integrate the subject of this paper into a running Annex or introduce a new Annex on the Efficiency of Domestic Hot Water Production.

6 REFERENCES

[1] Braber, Geelen, Kleefkens (2014); “Micro Heat Pumps in Hybrid – Low Temperature District Heating Concepts”; IEA Heat Pump Conference, Montréal, May 12-16 2014

[2] CBS (Statistics Netherlands), StatLine 2009

[3] Eco-Design - Boilers and water heaters: Draft regulations for boilers (Lot 1) and water heaters (Lot 2)

[4] Groot, et al., (2008). “Configuraties en optimalisaties van het warmtenet in Amsterdam” CE Delft, April 2008,

[5] Marquart, de Lange (2013); “Monitor energiebesparing gebouwde omgeving 2012”, Versienummer 2013-11; AgentschapNL, Utrecht, October 29th 2013