Appendix 9: Supporting information on Sankey diagram for residential HVAC

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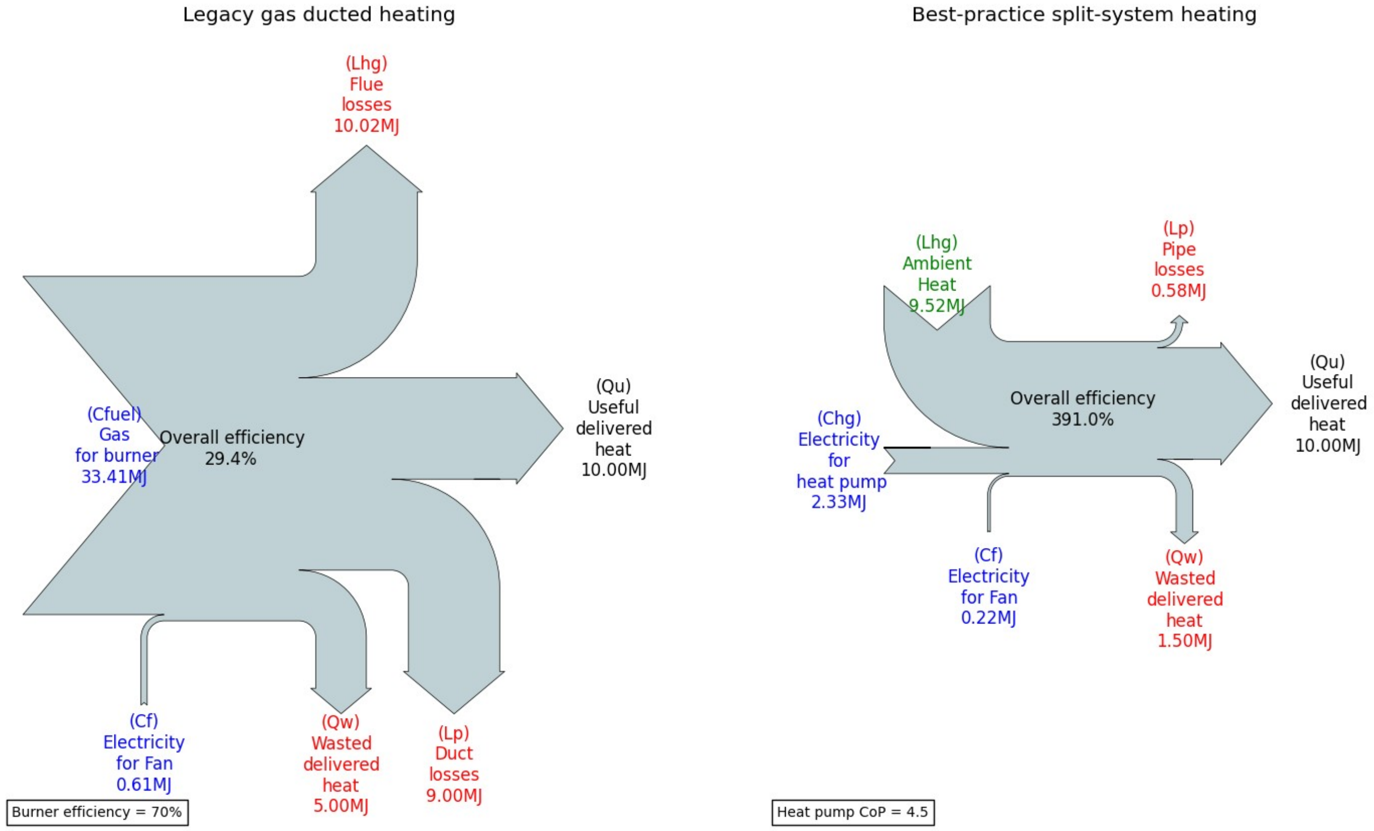
This Appendix provides supporting information on the methods and assumptions used in the generation of the Sankey diagram at Section 3 which depicts the relative efficiencies of a legacy gas ducted heating system, and a best-practice split-system heating system.

The diagram from Section 3 is reproduced here, including labels to help identify the individual energy flows.



Space heating relative efficiency: gas ducted *vs* split system heat pump.

General Method

The method of applying Sankey diagrams to HVAC is broadly based on the work by Perez-Lombard et al 2011 [1]. The intention is to compare and contrast the performance of a domestic legacy gas ducted heating system with a contemporary, well-installed split-system heat pump heating system. The rationale being that many such installed gas systems exist that could be replaced by heat pump systems. Comparing new with old is done in this context, and it is acknowledged that well-installed gas ducted systems could be more efficient that the system depicted here, although the general pattern of losses will be broadly similar.

Wasted delivered heat. The delivered energy from the heating systems is notionally divided between usefully delivered heat (Qu) and wasted delivered heat (Qw). This reflects the reality that a non-trivial proportion of the heated air delivered to the room might be wasted because of the following:

- *Poor mixing*. If the heated air is not sufficiently well mixed in the room, then buoyant warm air will pool at ceiling level an be returned to the return air of the system;

- *Balance loss*. Not all delivered warm air makes it way back to the return air because of unsealed opening (windows, vents, doors, cracks) and because the system may introduce some fresh air which necessarily displaces some warm air to outside;
- *Conditioning of useless space*. The system design may lead to inadvertent heating of spaces like hallways simply because of the requirements of the return air path;

Gas ducted system

The left-hand Sankey diagram depicts a gas heating system with the following broad characteristics:

- ten to 15 years old;
- ceiling ducts and registers, with some small level of leakage consistent with its age;
- fan power 330W (based on measurement and report by Tim Forcey (April 2013) of an 18kW_t Brivis85. Installed in house with 8 registers.)[5];
- 2.8m ceiling;
- return air in ceiling;

The following energy balance relationship is observed:

```
Cfuel + Cf =  Lhg + Qu + Lp + Qw
```

1. Nb = Burner efficiency
2. Cf = Fan input energy
3. Cfuel = Fuel input energy
4. Lhg = Flue losses
5. Qa = Ambient heat
6. Qw = Wasted delivered heat
7. Qu = Useful delivered heat
8. Lp = Pipe/Duct loss

Assumptions

Wasted delivered heat. It is assumed that one third of the delivered heat is wasted because all the three factors leading to waste of delivered heat (see above) apply in a typical ducted installation. In ducted systems the location of return air might be in a central hallway at ceiling level. Also the delivery through ceiling vents typically gives poor mixing to floor level. These factors combine to cause a large proportion of the delivered heat to be transferred at ceiling level via un-occupied spaces back to the return air inlet. Furthermore in ducted arrangements, the pressure difference between the vent and return air, plus the fresh air balance, will necessarily lead to heated air being pushed out though openings to the outside air.

Fan energy. Central ducted systems need large electric fan units. The ratio of gas energy to fan energy[5] is 18:0.33 = 54. The input gas energy, for every 10MJ usefully delivered is about 33MJ. So a reasonable estimate for fan energy in this model is 33/54 = 0.61MJ.

Pipe loss. It is assumed that 38% of the energy into the ducts is lost before it reaches the vent. This is a mid-range estimate based on the work by Palmer[4] who reports:

> "The pre-retrofit testing showed energy losses due to ductwork of between 26 and 58 percent, reducing to losses of between 10 and 18 percent after the replacement of the ductwork. Including the gas furnace (heater) efficiency, the pre-retrofit total system efficiency ranged from 30 percent, up to 69 percent. The post-retrofit system efficiency, including gas furnace, was between 50 and 76 percent. On average, the improvement of the system efficiency of the systems, in terms of energy delivered into the living space relative to the natural gas consumed, was 30 percent for the systems that were more than 15 years old, and 14 percent for the systems that were less than 15 years old."

Other useful sources on energy loss in ducts are Fricker & Johnson [6] and EES [7].

Burner efficiency. It is assumed that the thermal efficiency of the burner is 70%. This is based on an understanding that newer conventional burners achieve 80% - 85%, and that burner efficiency degrades over time. Under AS4556:200, 70% efficiency corresponds to an appliance energy rating of 3 stars[8].

Electric heat pump system

The right-hand Sankey diagram depicts a split-system heat pump heating system with:

- multi-split configuration, serving multiple rooms from a single external system;
- age less than three years;
- wall-mounted internal units;
- average heating CoP of 4.5;
- care taken to ensure refrigerant pipe runs are fully and properly insulated to standards.

The following energy balance relationship is observed:

```
Lhg+Chg+Cf = Lp + Qu + Qw
CoP=(Qu+Qw)/(Chg+Cf)
```

1. Cf = Fan
2. Chg = Heat pump
3. Lhg = Ambient heat
4. Qw = Wasted delivered heat
5. Qu = Useful delivered heat
6. Lp = Pipe loss

Assumptions

CoP. The heat pump is assumed to operate with an average heating coefficient of performance of 4.5. This is a reasonable typical value for the better-available systems.

Fan energy The indoor fan consumes energy equivalent to 1.5% of delivered energy. This is a guess based on the observation of the author that the indoor fan of a medium-sized split system consumes less than 50W on a medium setting.

Wasted delivered. It is assumed that 15% of the heat delivered into the room is wasted because of a combination of a) bouyancy effects, b) draughts, and c) incidental heating of un-used space.

Pipe loss. It is assumed that energy equating to 3% delivered energy is lost through refrigerant pipes.

How the diagram was generated

The diagram was generated programatically using the Python[2] programming language and a free graphics library called Matplotlib [3]. The code is shown below.

```
#!/bin/python
# name:  aircon_sankey.py
# description:  Generate two Sankey diagrams representing the energy flows
#               in two heating systems.
# author:  Richard Keech <richard.keech@gmail.com>
# date:    2013-01-16

#Refer: "The map of energy flow in HVAC systems", Luis Perez-Lombard a, Jose Ortiz b, Ismael R. Maestre c, 2011,
Applied Energy

import numpy as np

import matplotlib
matplotlib.use('AGG')
import matplotlib.pyplot as plt
from matplotlib.sankey import Sankey
from mpl_toolkits.axes_grid.anchored_artists import AnchoredText

def add_at(ax, t, loc=2):
    fp = dict(size=10)
    _at = AnchoredText(t, loc=loc, prop=fp)
    ax.add_artist(_at)
    return _at

plotfilename='aircon_sankey.png'

fig = plt.figure(figsize=(18,10))

a1 = fig.add_subplot(1, 2, 1, xticks=[], yticks=[], title="Legacy gas ducted heating")
a2 = fig.add_subplot(1, 2, 2, xticks=[], yticks=[], title="Best-practice split-system heating")
fig.subplots_adjust(hspace = 0.0001)
#==================================================================================
# Gas ducted heating
# Qu  = Useful delivered heat
Qu=10.0
# Qw  = Wasted delivered heat
Qw=0.5*Qu
# Cf  = Fan input energy.  0.61MJ based on ratio of gas_input_energy:fan_energy of 54 (18kW/0.33kW)
# and knowing that Cfuel ~ 33MJ.
Cf=0.61
# Lp  = Pipe/Duct loss
Lp=0.6*(Qu+Qw)
# Nb  = Burner efficiency
Nb=0.7
# Cfuel   = Fuel input energy
Cfuel=(Qu+Qw+Lp-Cf)/Nb
# Lhg = Flue losses
Lhg=Cfuel*(1-Nb)
# Na  = overall efficiency
Na=Qu/(Cfuel+Cf)

# Basic energy balance:
# Cfuel + Cf = Lhg + Qu + Lp + Qw
# => Lhg = Qu+Qw+Lp-Cfuel-Cf

sankey1=Sankey(
    ax=a1,
    format='%.2f',
    scale=0.6/Qu,
    flows=[Cf, Cfuel, -Lhg, -Lp, -Qw, -Qu],
#    labels=['(Cf)\nElectricity\nfor Fan', '(Cfuel)\nGas\n for burner', '(Lhg)\nFlue\nlosses', '(Lp)\nDuct\nlosses',
"(Qw)\nWasted\ndelivered\nheat", '(Qu)\nUseful\ndelivered\nheat'],
    labels=['Electricity\nfor Fan', 'Gas\n for burner', 'Flue\nlosses', 'Duct\nlosses', "Wasted\ndelivered\nheat",
'Useful\ndelivered\nheat'],
    pathlengths=[0.5,0.7,0.5,0.6,0.4,0.1],
    orientations=[-1, 0, 1, -1, -1, 0],
    unit='MJ',
    patchlabel="Overall efficiency\n"+str(round(Na*1000)/10)+"%",
    offset=0.3,
    ).finish()

sankey1[0].texts[0].set_color('blue')
sankey1[0].texts[1].set_color('blue')
sankey1[0].texts[2].set_color('red')
sankey1[0].texts[3].set_color('red')
sankey1[0].texts[4].set_color('red')
sankey1[0].texts[5].set_color('black')
```

```
add_at(a1,"Burner efficiency = 70%",loc=3)
a1.axis('off')
#===================================================================================
#  Heat pump

# CoP = coefficient of performance
CoP=4.5
# Qu  = Useful delivered heat
Qu=10
# Cf  = Fan
Cf=0.015*(Qu+Qw)
# Qw  = Wasted delivered heat
Qw=0.15*Qu
# Lp  = Pipe loss
Lp=0.05*(Qu+Qw)

#Basic energy balance:
#Lhg+Chg+Cf = Lp  + Qu + Qw
#CoP=(Qu+Qw)/(Chg+Cf)
# Chg = Heat pump input energy
Chg=((Qu+Qw)/CoP)-Cf
# Lhg = Ambient heat
Lhg=Lp+Qu+Qw-Chg-Cf
# Na  = overall system efficiency
Na=Qu/(Chg+Cf)

sankey2=Sankey(
    ax=a2,
    format='%.2f',
    scale=0.6/Qu,
    flows=[Cf, Chg, Lhg, -Qw, -Lp, -Qu],
#    labels=['(Cf)\nElectricity\nfor Fan', '(Chg)\nElectricity\nfor\n heat pump', '(Lhg)\nAmbient\nHeat',
"(Qw)\nWasted\ndelivered\nheat", '(Lp)\nPipe\nlosses', '(Qu)\nUseful\ndelivered\nheat'],
    labels=['Electricity\nfor Fan', 'Electricity\nfor\n heat pump', 'Ambient\nHeat', "Wasted\ndelivered\nheat",
'Pipe\nlosses', 'Useful\ndelivered\nheat'],
    pathlengths=[0.3,0.0,0.3,0.3,0.1,0.15],
    orientations=[-1, 0, 1, -1, 1, 0],
    unit='MJ',
    patchlabel="Overall efficiency\n"+str(round(Na*100))+"%",
    offset=0.3,
    ).finish()

sankey2[0].texts[0].set_color('blue')
sankey2[0].texts[1].set_color('blue')
sankey2[0].texts[2].set_color('green')
sankey2[0].texts[3].set_color('red')
sankey2[0].texts[4].set_color('red')
sankey2[0].texts[5].set_color('black')

add_at(a2,"Heat pump CoP = 4.5",loc=3)
a2.axis('off')

plt.savefig(plotfilename, bbox_inches='tight')
```

References

1. Luis Perez-Lombard a, Jose Ortiz b, Ismael R. Maestre c, “The map of energy flow in HVAC systems,” ‘Applied Energy’ , 88, 2011: p5020-5-31.
2. http://www.python.org/
3. http://matplotlib.org/
4. Palmer, G., “Field study on gas ducted heating systems in Victoria”, September 2008, BEng thesis, RMIT, http://www.paltech.com.au/datasheets/Gas_Ducted_Report_DRAFT.pdf
5. Forcey, T., personal communication April 2013.
6. Fricker & Johnson, “Testing and modelling of flexible air duct heat losses”, Ecolibrium Magazine, March 2009, http://www.airah.org.au/imis15_prod/Content_Files/EcoLibrium/2009/March09/2009-03-01.pdf
7. Energy Efficient Strategies (EES), “Energy Use in the Australian Residential Sector”, 2008, page 15.
8. Equipment Energy Efficiency Program of Australian Federal Government, “Gas Ducted Heaters: Product Profile”, 2011, http://www.energyrating.gov.au/wp-content/uploads/2011/04/201102-gas-ducted-heaters.pdf