Smart thermostatic valves based heat generator control to cut heating bills

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Abstract.
The following work aims at demonstrating how a smart thermostatic (radiator) valve network can be used to reduce heating costs by controlling the heat generator (heat-pump, gas boiler, ...) in a more efficient way. Currently, a large proportion of heat generators is controlled by the means of a heating curve, or a similar rule-based logic that mostly rely on outdoor temperature or single point indoor temperature measurements. These simple control laws are in general commissioned to minimize the number of complaints of "cold users". This results in high forward temperatures, that are energetically non-optimal as they create increased losses in the piping network and also have a negative impact on the heat generator efficiency. In the proposed data driven approach, a controller was developed to ensure that the radiators receive fluid with the lowest temperature possible, while satisfying the heating needs. To achieve this goal, smart thermostatic valves are used to monitor the radiator activity. The monitored information is used by a real-time algorithm to adapt the hot water temperature to continuously ensure user comfort. The solution was deployed in a multi-apartment building located in Neuchâtel (Switzerland). The solution has been running with success during the 2020-2021 heating season. The results point out that an average saving of 15% is obtained with respect to the baseline (i.e. heating curve) controller under similar conditions, without any degradation of comfort (under heating in particular). The system will now be deployed on 6 houses in Denmark and remain active at least until 2023.

Keywords. heat generator, control, smart thermostatic valves, radiator, mixing valve, data-driven heat controller
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1. Introduction

Space heating (SH) represents a significant part of the energy usage and thus CO_2 emissions. Nowadays, thermostatic valves, conventional or electronic [1] [2], are well established to allow for a well-controlled zone temperature. Nevertheless, to operate properly, the heat emitters, need to be supplied with a heating fluid of a high enough temperature.

Unfortunately, for residential buildings, as for most larger facilities, the heat generator (and mixing valves, if relevant) are still controlled by so called heating curves, which generally provide a linear relationship between the outdoor temperature and desired forward heating temperature. The commissioning of these controllers is in general performed to ensure some overheating, to guarantee user comfort and thus prevent complaints. This results in the generation of heating fluid at too high temperature, which is negatively impacting the coefficient of performance (COP) of the heat generator. In addition, the resulting losses in the distribution piping are also increased.

To overcome these issues, predictive algorithms coupled to optimization have drawn attention [3] [4] [5]. However, in general the commissioning both in terms of hardware to be deployed and software tailoring to be performed, prevent acceptance and thus replication.

In that context, we propose a novel approach that relies on the smart thermostatic valve (STV) information to control the heat generation. The underlying algorithm relies on the STV measured data to continuously adjust the forward temperature set-point. The method does not require complex commissioning (i.e. tuning of building models or control loops) and achieves energy savings in the order of 15% when compared to the baseline case, without compromising comfort.

The article is organised as follows:

- Section 2.1: highlights the concept
- Section 2.2: introduces the considered key performance indicators (KPI)
- Section 2.3: shows the test site located in the city of Neuchatel (Switzerland)
- Section 2.4: provides details about the test plan
- Section 3: provides the obtained results, per KPI

2. Method

2.1 The concept

A large proportion of heat generators are controlled by the means of a heating curve (i.e. the system is configured to produce water at a temperature that is inversely proportional to the outside temperature), or a similar rule-based logic, for instance night set-back. These simple control laws are in general commissioned to minimize the number of complaints of "users feeling cold". In other words, over-heating is performed to be on the safe side and avoid a technician to be dispatched. In consequence, it is energetically non-optimal. In addition, the method provides no adaptation to modifications in user habits or specific needs. This results in increased losses in the piping network as well as heat generators running at lower efficiencies, as shown in **Fig. 1** (left). Indeed, gas boilers and heat-pumps have higher coefficient of performance (COP) at lower temperatures.

In the chosen approach, **Fig. 1** (right), the radiators receive the minimal temperature required to satisfy the heating needs. To achieve this goal, smart thermostatic valves (STV), shown in **Fig. 2**, are used to monitor the radiator activity, such as the valve opening, which reflects the actual heating needs.

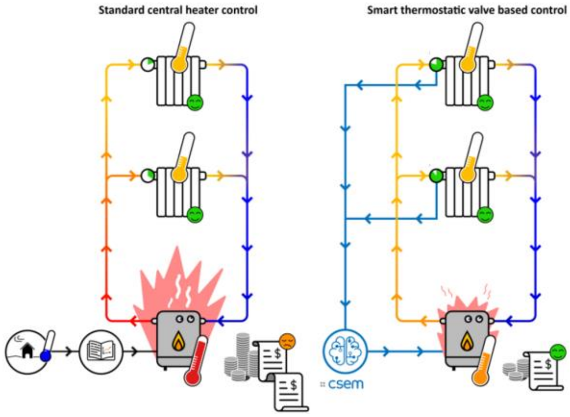

Fig. 1 – Standard central heater control (left), STV based data-driven heat control (right)

The monitored information is used by a real-time algorithm to adapt the hot water temperature to continuously ensure user comfort.

Fig. 2 – Smart Thermostatic Valve (STV)

In previous work [6], validation in simulation showed average savings of 8% on gas condensing and around 18% for heat pumps.

Deployment is simplified as the only needed hardware are STVs and the necessary communication gateways.

A building in Neuchâtel was equipped with all needed material to validate the concept (valves, energy meters & communication gateway). The solution has been running with success during the 2020-2021 heating season.

In the novel approach, the goal of the data-driven heat controller is to reduce the supply heat temperature of each heating circuit based on the real time data provided by the radiator valves. Doing so allows to provide the rooms with the right amount of heat and accordingly lower the needs at the generation level.

2.2 KPI

Key performance indicators (KPI) are defined to evaluate the thermal energy savings of the proposed method compared to the baseline implementation, while keeping desired comfort for the inhabitants. Following KPIs are defined to assess the thermal energy and comfort:

- **Energy KPI – Daily thermal energy versus average outdoor temperature**. Daily thermal energy per heating circuit is computed as the integration over one day of the thermal power at heating circuit mixing valve level. The total energy consumed at building level is the sum of energy at mixing valves level.

- **Comfort KPI – Underheating and overheating versus average outdoor temperature**. Under / overheating is computed as the difference between the measured room temperature T_{room} and the valve temperature set-point T_{sp}. Daily underheating is the integration over one day of the $\min(T_{room} - T_{sp}^{clip}, 0)$ averaged over all valves, while daily overheating is the integration over one day of the $\max(T_{room} - T_{sp}^{clip}, 0)$ averaged over all valves. To avoid artifacts from out-of-range values from the valve temperature set-point the feasible values were limited in between 16°C and 24°C, i.e. $T_{sp}^{clip} = \text{clip}(T_{sp}, 16, 24)$.

These two KPIs evaluate the energy and comfort of the proposed solution. Results are shown in Section 3.

KPIs are computed for both, the baseline, and the proposed solution with the data-driven heat controller.

For the baseline, a standard heating curve is used to drive the three heating circuits, and in consequence the heat generator.

2.3 Test site

The test site is a mixed (residential and tertiary) building located in the city of Neuchatel (Switzerland). The ground floor is composed of an office and two shops, the four floors host six flats.

The building heat is generated by a gas condensing boiler (Logamax from Buderus that can provide up to 82kW) that serves for space heating and domestic hot water production. Given the building layout, three independent heating circuits (HC1, 2 and 3) each equipped with an independent mixing valve and circulation pump are used (see **Fig. 3**). Each heating circuit is equipped with an individual heat meter, in addition, domestic hot water is also monitored (and removed from space heating).

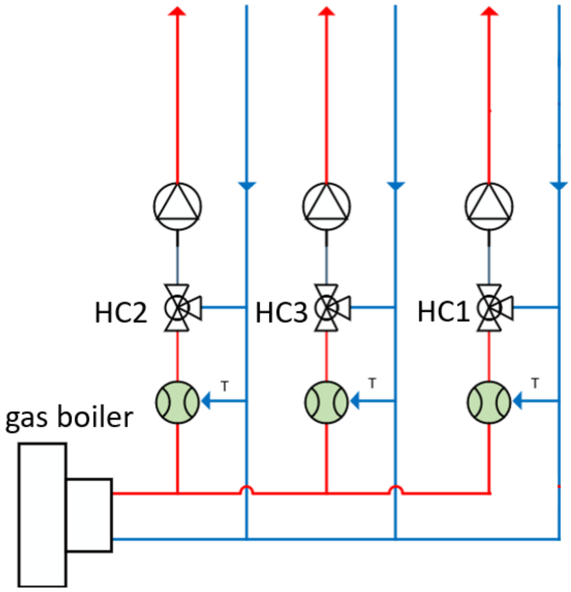

Fig. 3 – Building heat generation and distribution layout showing three heating circuits (HC2, HC3 and HC1 from left to right).

The gas boiler default heating curve set-point can be bypassed thanks to the KM200 gateway from Buderus. This device allows setting the target forward temperature of each heating circuit independently. The boiler oversees generating the heat and driving the mixing valves. For information, the default heating curve is defined by an inversely proportional relationship between the desired forward heating temperature and the outdoor temperature.

The heat emission is ensured by standard steel radiators. The latter were equipped with smart thermostatic valves (SmartDrive MX from HORA and Vicki from MClimate). STV are installed on all radiators, with 14, 5 and 50 units respectively for each heating circuit (i.e. HC2, HC3, and HC1). Among the measured values, the room temperature, room temperature set-point and valve percentage opening are the most critical for the algorithm and results analysis.

A high-level view of the data exchanges is provided in **Fig. 4**. Radiator status is measured by the valves (STV), this information is transmitted to a database located at CSEM. The algorithm is executed on a dedicated server and the computed heating circuit set-points are sent to the KM200 gateway.

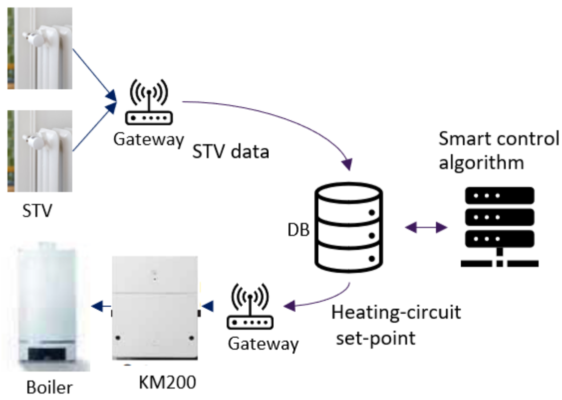

Fig. 4 – Cloud controller

2.4 Test protocol

To evaluate the proposed STV data-driven heat controller and compare it with the baseline, measurements were taken during the winter-spring 2021 seasons from January 15th to June 31st, 2021.

During the preliminary development stage, initial measurements from 15.01.2021 to 12.02.2021 are composed only of baseline data. Then, once the data-driven control algorithm was getting ready, the data-driven heat controller was gradually activated on each heating circuit:

- HC2 starting from 12.02.2021
- HC3 starting from 03.03.2021
- HC1 starting from 23.04.2021

In addition, reverting time to time to baseline operation to have a representative mix of baseline and experiment data spread over a range of outdoor temperature from winter to spring was done[1].

Analysis can be further discriminated between day and night schedule for each heating circuit. The day/night schedule refers to the settings entered by the users at valve level. These settings remain the same during the baseline and optimized control. The configuration of each heating circuit with the number of radiators, day schedule, number of baseline days and experiment days are summarized in **Tab. 1**.

[1] In the follow up heating season, a monthly switching between baseline and data-driven heat control will be done to better analyse and compare both approaches.

Tab. 1 – Heating circuits configuration

Settings	**HC2**	**HC3**	**HC1**
# Radiators	14	5	50
# Baseline days	30	19	48
# Experim. days	69	56	38
Day schedule	9-22h	7-19h	9-22h

Heating circuits HC2 and HC1 supply living spaces with one and six apartments respectively. Heating circuit HC3 supplies a workshop for daily activities.

3. Results

Results are computed for the winter-spring 2021 heating season with energy and comfort KPIs defined in Section 2.2 and test protocol with measurement periods presented in Section 2.4.

3.1 Energy KPI

Energy KPI are computed for each heating circuit with day/night discrimination. Results for daily energy KPI are represented versus the outdoor temperature. Unit of energy KPI is in kWh per day [kWh/d].

The result for the whole building, is provided in **Fig. *5***, where the energy is normalized at 0°C outdoor temperature, in reference to the baseline, and each heating circuits aggregated, so that the whole building energy can be compared between the proposed optimized solution and the baseline. Qualitatively, the thermal power consumption is reduced by 15% for the proposed solution based on the regression at 5°C outdoor temperature.

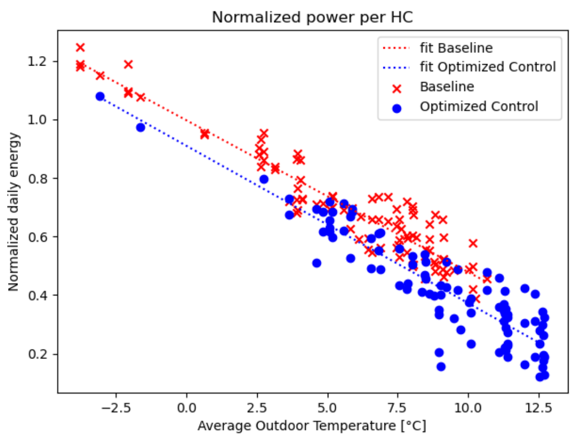

Fig. 5 – Normalized energy results for the whole building (i.e. Energy of HC1, 2 and 3 are normalized at 0°C outdoor temperature, in reference to the baseline, and aggregated)

Energy KPI for HC2, HC3 and HC1 are shown in the appendix in **Fig. 6**, **Fig. 7** and **Fig. 8**, respectively. One can observe a clear reduction of the thermal energy consumption, for the three heating circuits.

Experimental results from heating circuits HC2 and HC3 are promising. Experimental data for heating circuit HC1 are limited, as it was put in service later in the heating season.

3.2 Comfort KPI

Comfort KPI are computed for each heating circuit. Results for underheating and overheating errors KPIs are represented versus the outdoor temperature. Unit of under/overheating error is in Kelvin hour per day [Kh/d].

Global underheating and overheating averaged over all baseline days and experiments days are computed and summarized in **Tab. 2** for underheating and in **Tab. 3** for overheating.

Underheating KPI for HC2, HC3 and HC1 are shown in the appendix in **Fig. 9**, **Fig. 10** and **Fig. 11**, respectively, while overheating KPI for HC2, HC3 and HC1 are shown in **Fig. 12**, **Fig. 13** and **Fig. 14**, respectively.

Tab. 2 – Comfort KPI for underheating

Underheating	**HC2**	**HC3**	**HC1**
for baseline	-0.72	-0.88	-0.31
for experiment	-0.78	-0.93	-0.19

Tab. 3 – Comfort KPI for overheating

Overheating	**HC2**	**HC3**	**HC1**
for baseline	0.26	0.48	0.64
for experiment	0.34	0.46	1.22

Overall observation shows that the underheating and overheating are similar between baseline and experiments for heating circuits HC2 and HC3. For underheating, a value of -0.5 is to be interpreted as: “the average of the valves of the considered heating circuit are 0.5K below the desired set-point over one day”.

It is worth pointing out that the savings mentioned in the previous section are not linked to the underheating. Indeed, for HC2 and HC3 the underheating difference between baseline and experiments is only 0.06Kh/day and 0.05Kh/day. Such small differences do not induce 15% energy reduction. Indeed, on average one expects a 1°C indoor temperature difference to impact the energy expenditure by ~7%.

For heating circuit HC1, there is less underheating and more overheating, showing there is a potential for even more thermal energy savings. This result was to be expected, as it was agreed with the building owner that the experiments should be rather conservative in terms of energy savings to prevent any potential discomfort to the tenants.

4. Conclusion

The STV data driven central heating controller was successfully deployed in a real test site. The comparison to the baseline (heating curve) controller shows energy reduction in the order of 15% with no significative impact on comfort.

Future work is aimed to improve the data-driven heat controller with the help of an adaptive scheme to outperform the baseline controller for comfort, while maintaining the energy savings. This new controller will be deployed in six new test sites.

5. Acknowledgement

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6. Appendix

6.1 Energy KPI details

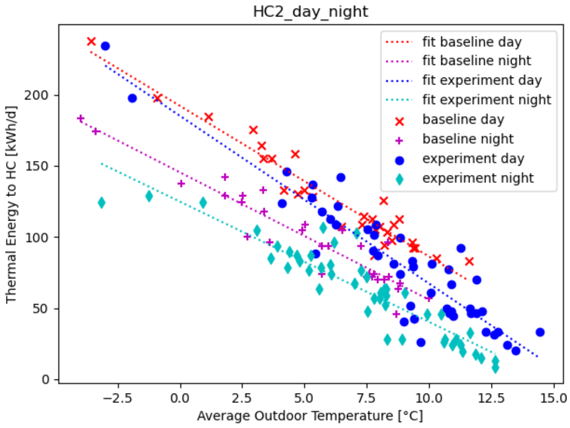

Fig. 6 – Energy KPI with day/night split for the HC2 riser with 14 radiators over 30 days of baseline and 69 days of experiment

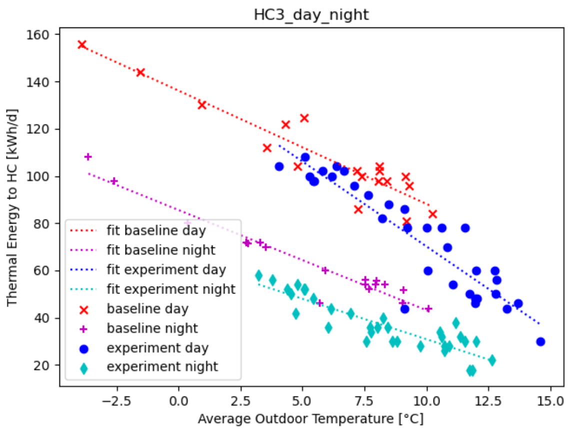

Fig. 7 – Energy KPI with day/night split for the HC3 riser with 5 radiators over 19 days of baseline and 56 days of experiment

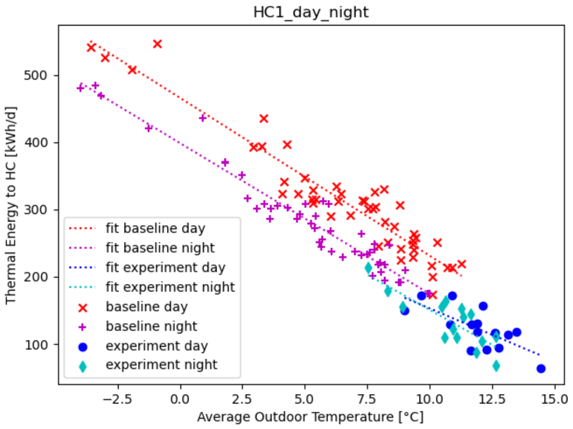

Fig. 8 – Energy KPI with day/night split for the HC1 riser with 50 radiators over 48 days of baseline and 38 days of experiment

6.2 Comfort KPI details

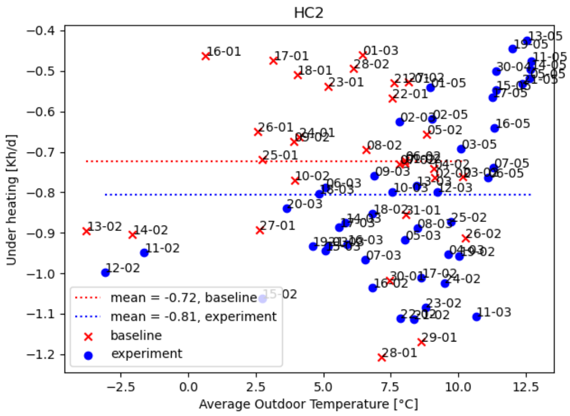

Fig. 9 – Underheating KPI for the HC2 riser with 14 radiators over 30 days of baseline and 69 days of experiment

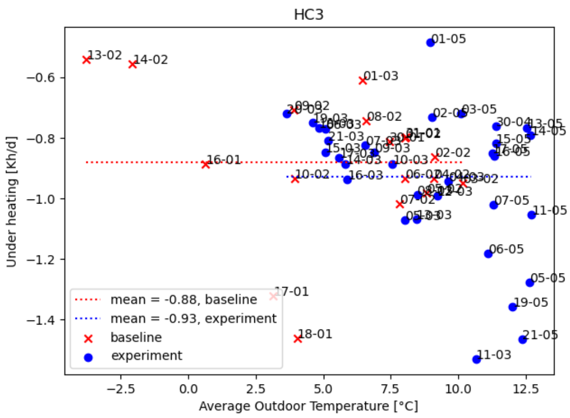

Fig. 10 – Underheating KPI for HC3 riser with 5 radiators over 19 days of baseline and 56 days of experiment

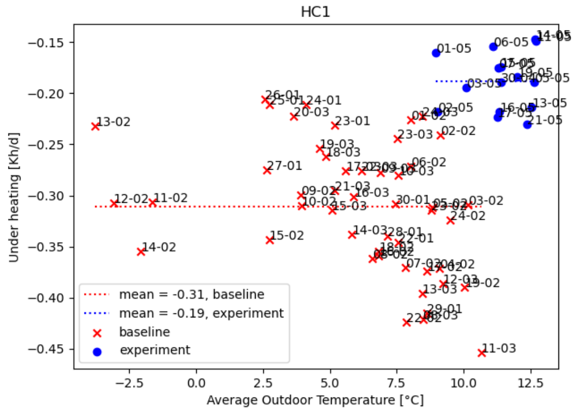

Fig. 11 – Underheating KPI for the HC1 riser with 50 radiators over 48 days of baseline and 38 days of experiment

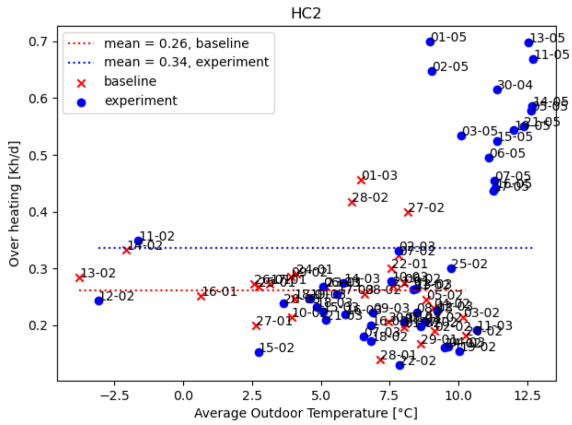

Fig. 12 – Overheating KPI for the HC2 riser with 14 radiators over 30 days of baseline and 69 days of experiment

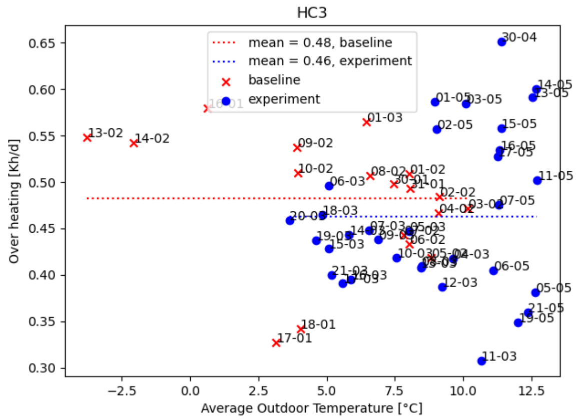

Fig. 13 – Overheating KPI for HC3 riser with 5 radiators over 19 days of baseline and 56 days of experiment

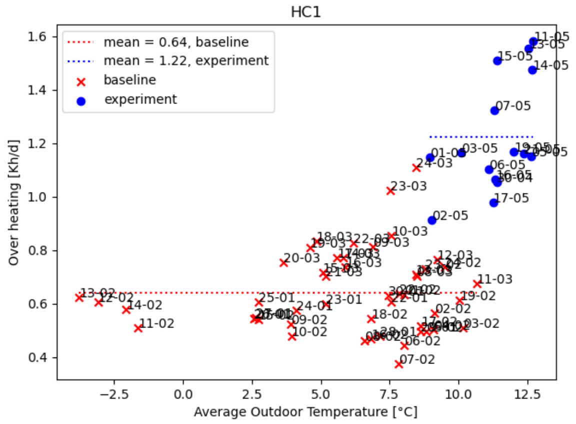

Fig. 14 – Overheating KPI for the HC1 riser with 50 radiators over 48 days of baseline and 38 days of experiment

7. References

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