Wednesday 28th April,2021

On the Design and Operation of Heat Pump Systems for Zero Carbon Districts

Master’s Thesis Defence Presentation

by

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Under Supervision of

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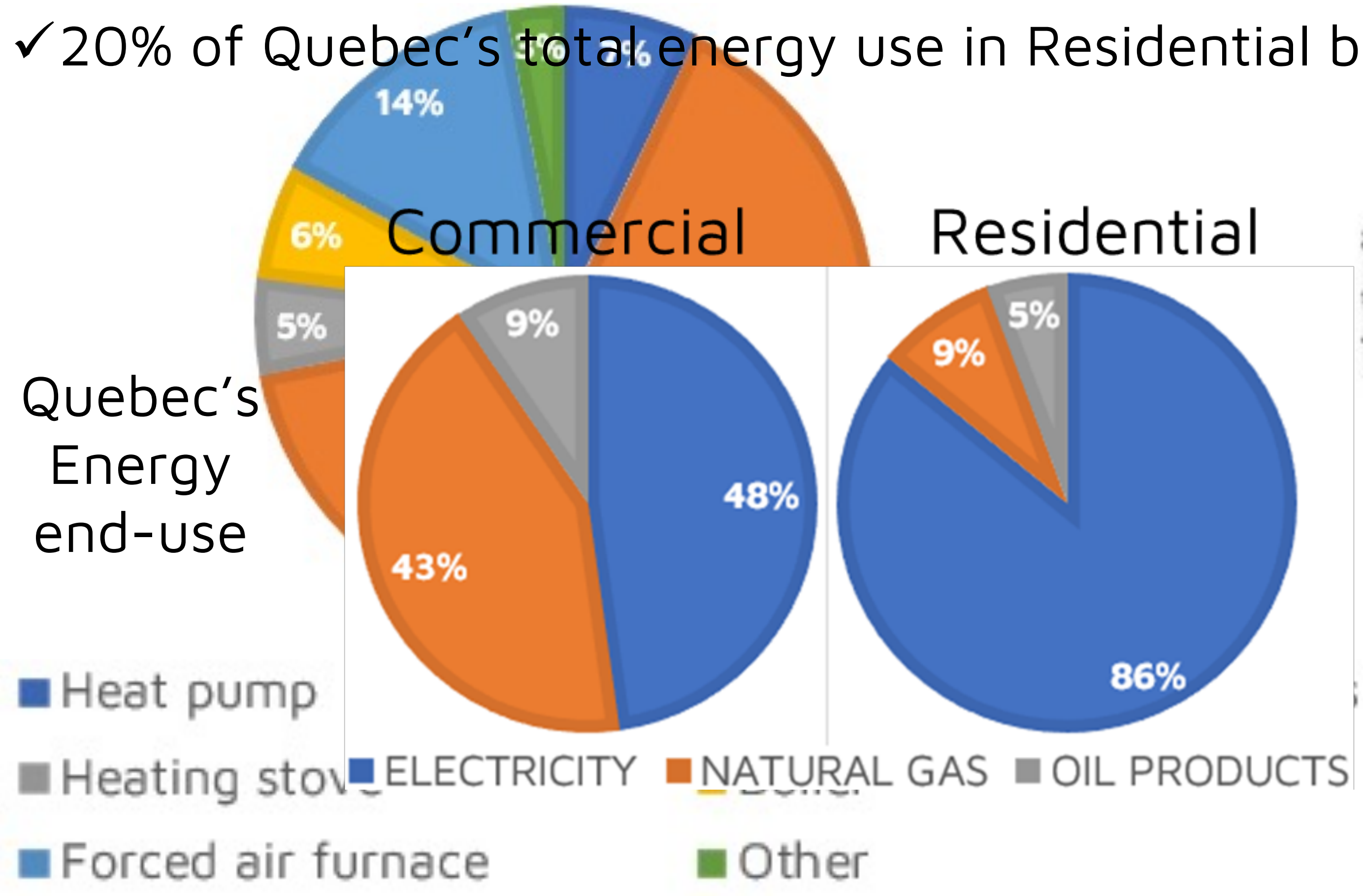
What is happening Energy-wise?

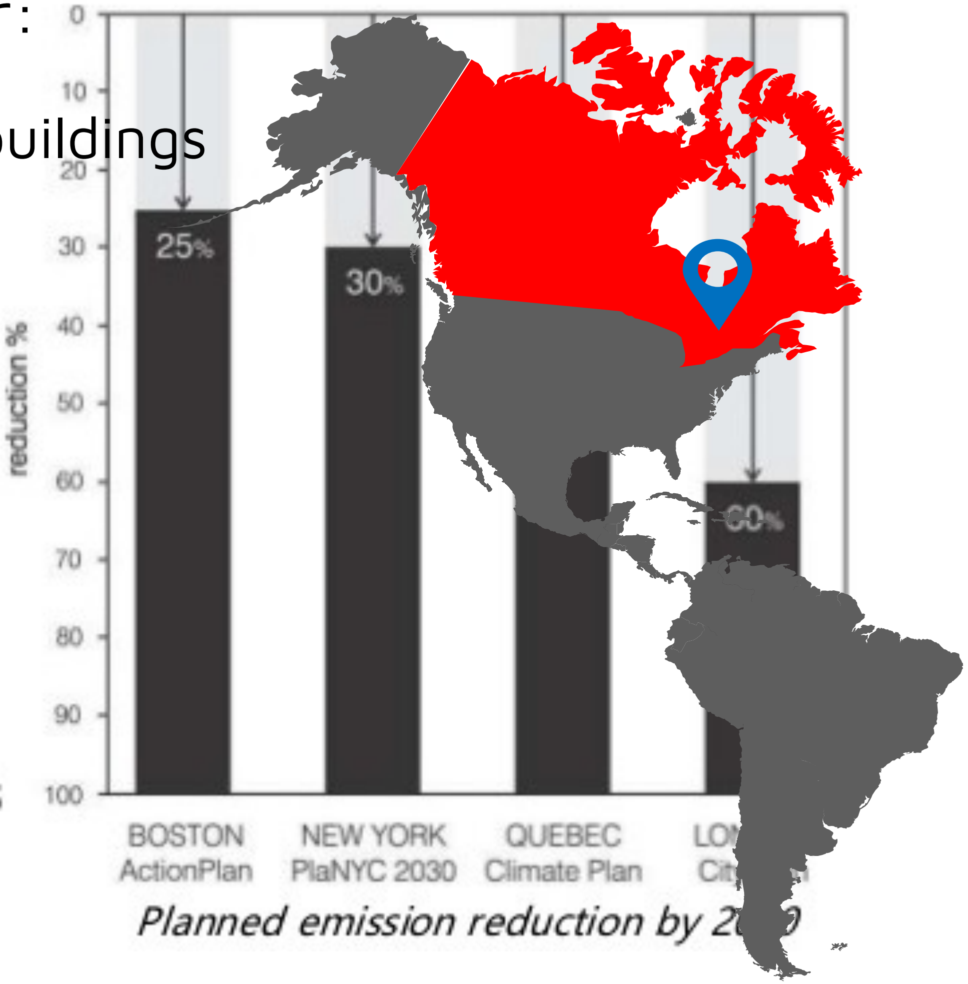
Statistics Canada & Canada Energy Regulator:

Quebec Households' Primary Heating System

✓20% of Quebec's total energy use in Residential buildings

Quebec's Energy end-use





Urban Energy System Modeling (UESM)

- Strategic Energy Planning
- Greenhouse Gas Emission reduction
- Sustainable Design

Single Building Energy Modeling

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District Scale Energy Modeling

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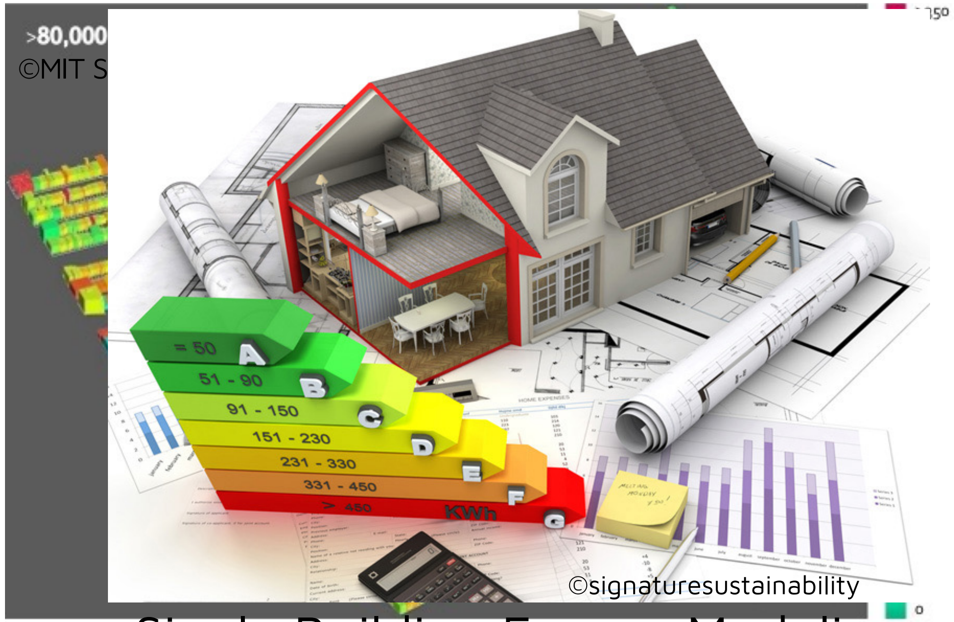
City Scale Energy Modeling



Single Building Energy Modeling
City Scale Energy Modeling

Urban Energy System Modeling (UESM)

❑Frameworks for energy modeling, planning and policy making

- Different applications/ focus (Demand, Supply, Waste,…)
- Various Capabilities (Scale, Temporal Resolution, Technology,…)
- Different approaches (Benchmarking, Optimization, Simulation, …)

AURORAxmp	EnergyPlus	STREAM
EnergyPLAN	eTransport	TRNSYS
ETM	HOMER	COMPOSE
HEAT+	INVERT/EE-Lab	EMCAS
INSEL	MESSAGE	E-OPT
OpenDSS	MODEST	City Energy Analyst
PyPSA	NEMS	GEMIS
SimStadt	PLEXOS	IKARUS
SynCity	RETScreen	LEAP
Urbs	STAR	Network Planner
CityInSight	TRACE	SIMPOW
CYME	SAM	UMI
PRIMES	SWITCH	

Names of commonly used UESMs

Literature review – UESM

Author	Overview	Focus/ Finding/ Suggestion
Connolly et al. 2010 [9]	Explored 37 UESMs	Proposing best UESMS fit for every application
Sinha et al. 2014 [10]	19 UESMs discussed in detail	Highlighted capabilities, limitations and future research areas of different UESMs
Ringkjøb et al. 2018 [11]	Detailed review of 75 UESMs	Categorized UESMs by general logic, spatiotemporal resolution and techno-economic parameters
Yazdanie et al. 2021 [8]	Explored 30 review studies including 61 UESMs	Fundamental review of gaps and improvement point in current tools
Hall et al. 2016 [12]	Review of 22 implemented UESMs	model purpose and structure, technological detail and mathematical approach

Literature review – Gaps

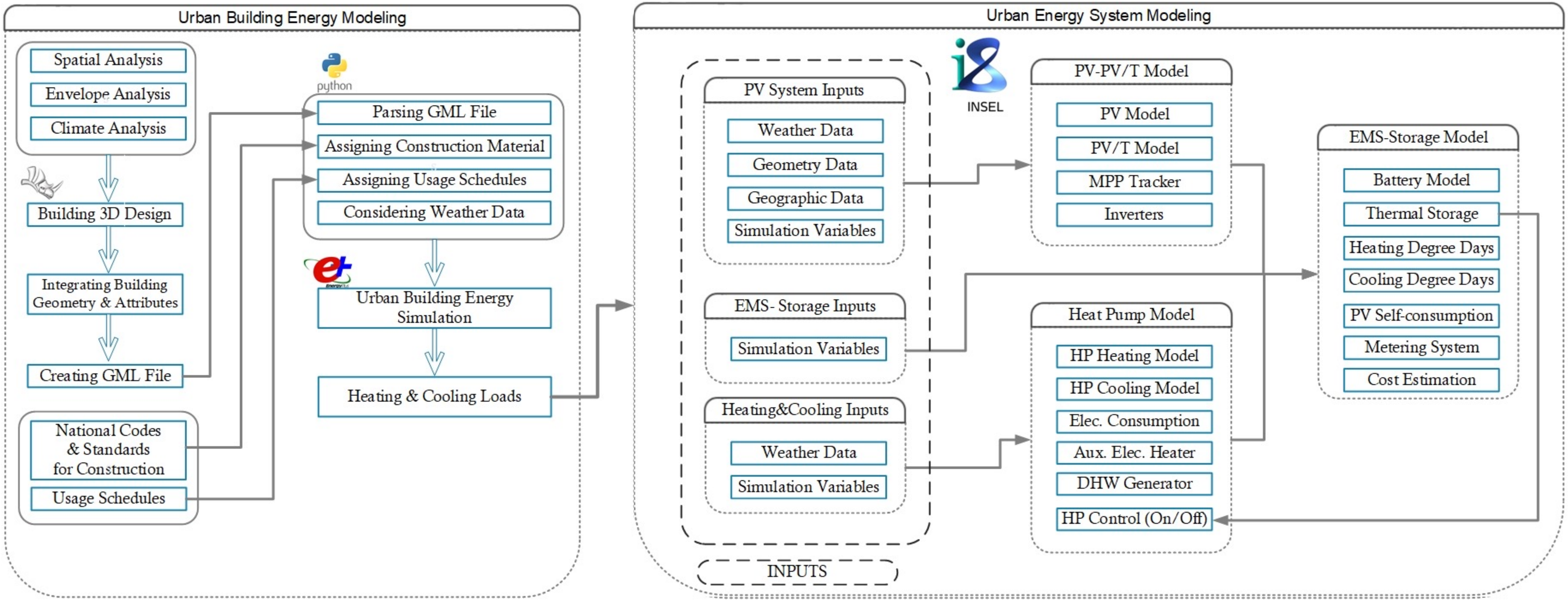
❑ Issues to be addressed in UESMs:

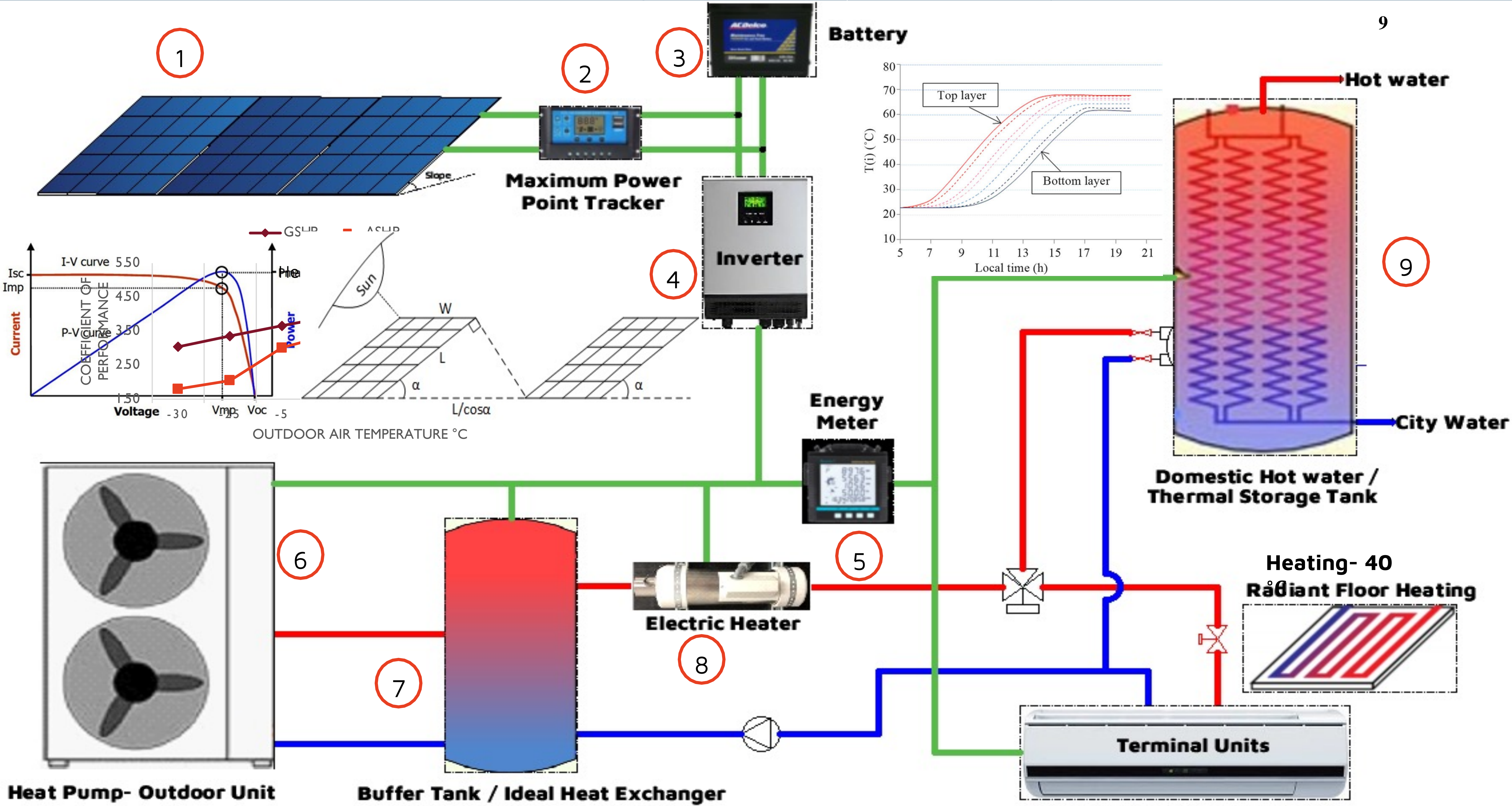
- Lack of adjustable temporal resolution regarding the problem and available data
- Lack of transparency and flexibility
- Not modeling demand (demand is an input)
- Inability to practice demand-side management strategies
- Energy system sizing is not automatized / Input by the user
- Not capturing Energy System Performance fluctuations in high temporal resolution

Research Focus- Objectives

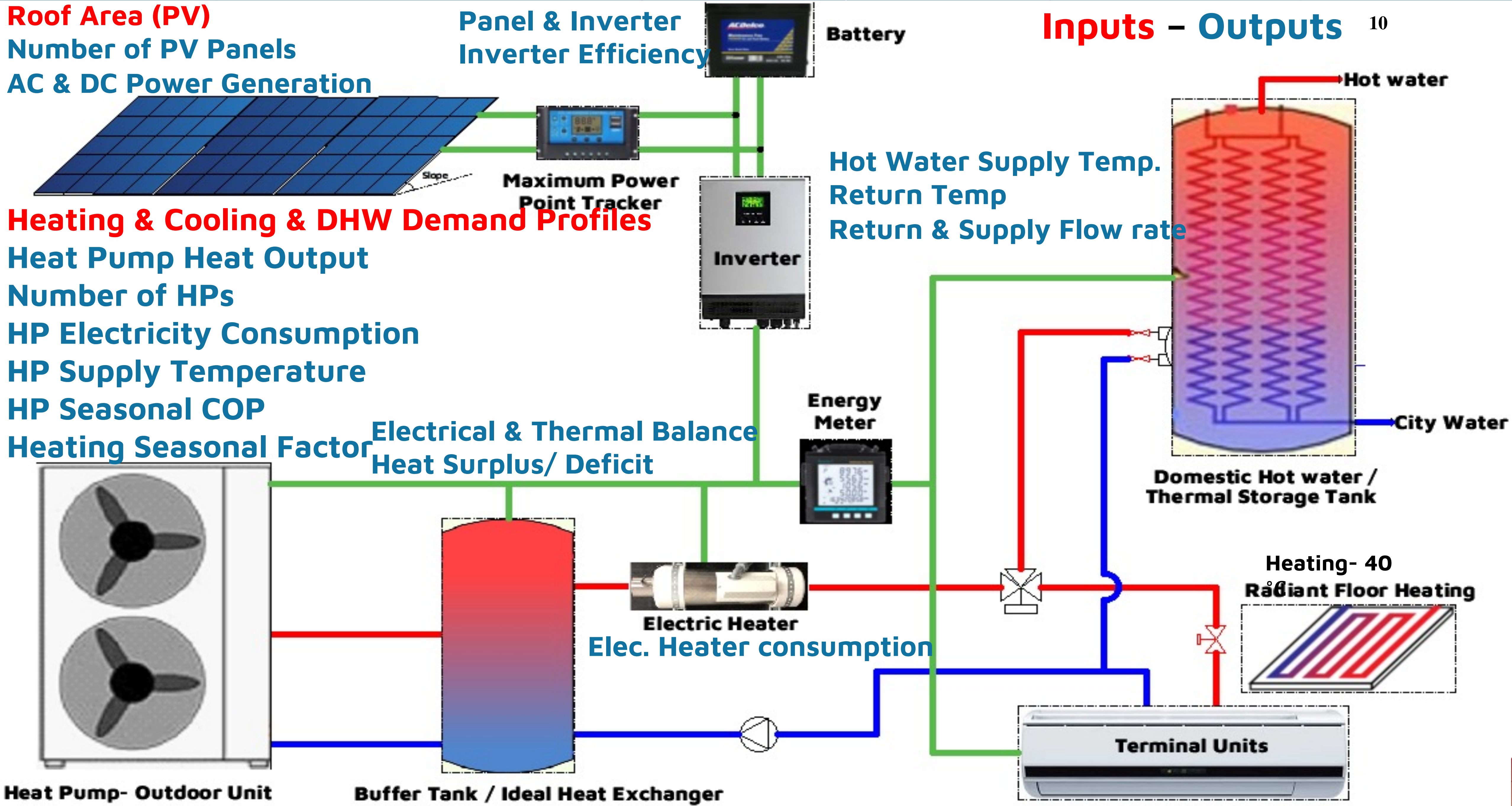
- Proposing an automated, flexible and transparent workflow Capable of:
  - Adjusting temporal resolution
  - Integrating demand and supply side
  - Selecting and sizing detailed energy system model components to supply heating, cooling and domestic hot water
  - Practicing demand-side management strategies
  - Performing Optimization and sensitivity analysis

Proposed Workflow



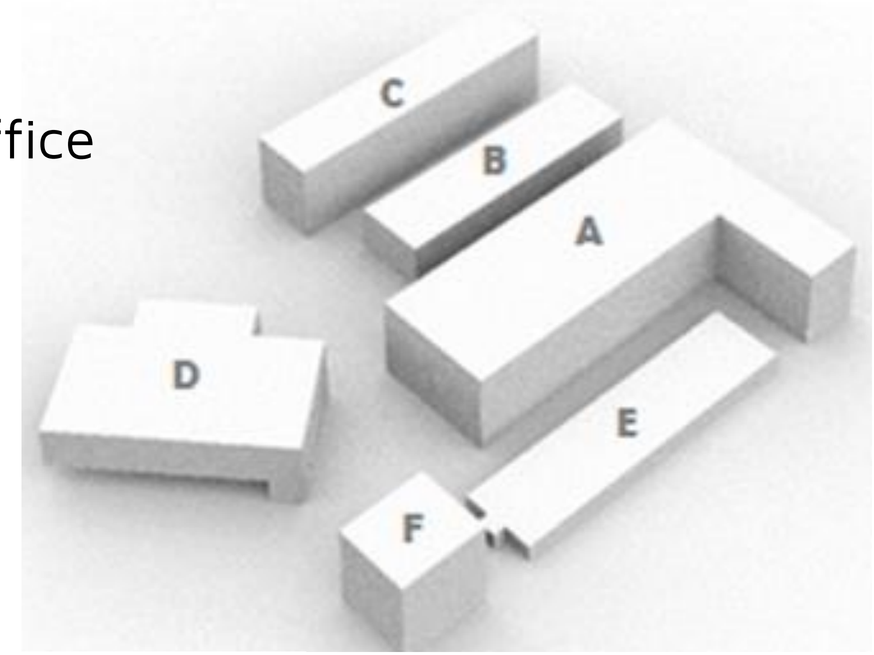

1
2
3
Battery
Maximum Power Point Tracker
Inverter
4
Top layer
Bottom layer
T(i) (°C)
Local time (h)
Hot water
9
Isc
Imp
I-V curve
P-V curve
Current
Power
Voltage
Vmp
Voc
GSHP
ASHP
COEFFICIENT OF PERFORMANCE
OUTDOOR AIR TEMPERATURE °C
Sun
W
L
α
L/cosα
Slope
Energy Meter
5
City Water
Domestic Hot water / Thermal Storage Tank
6
7
Electric Heater
8
Heating- 40 °C
Radiant Floor Heating
Terminal Units
Heat Pump- Outdoor Unit
Buffer Tank / Ideal Heat Exchanger

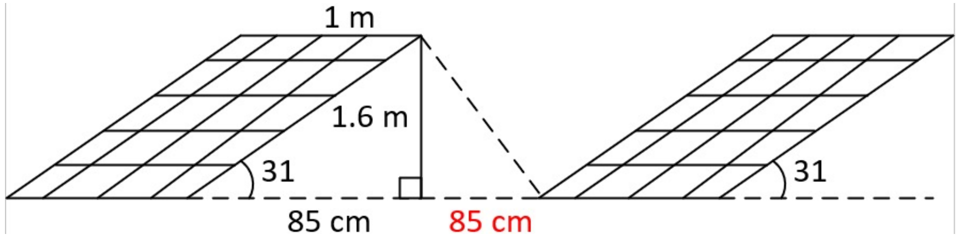
Inputs – Outputs



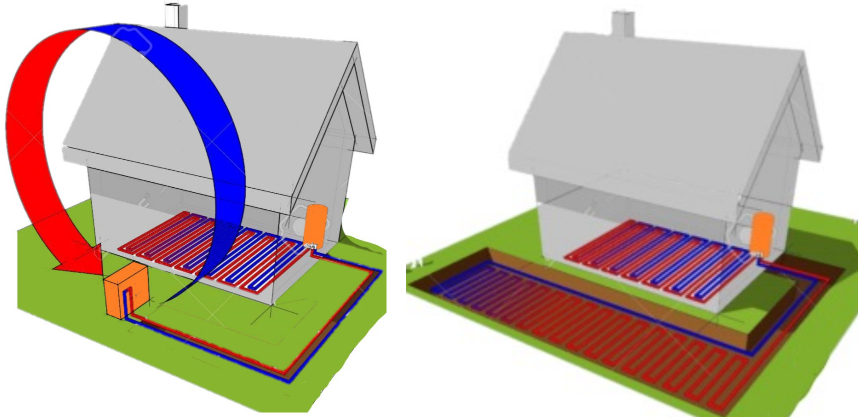
Case study 1– Dominion Bridge 1st Objective

- Dominion Bridge district, Lachine, Montreal
  - 6 mixed-use buildings, 277,000 sqm, 90% residential, 10% office
- Energy system design parameters
  - Low-temp heating / High-temp cooling
  - PV covers 65% roof area, Slope 31 degree
- Objectives
  - Energy positivity potential
  - Air Source & Ground Source HP





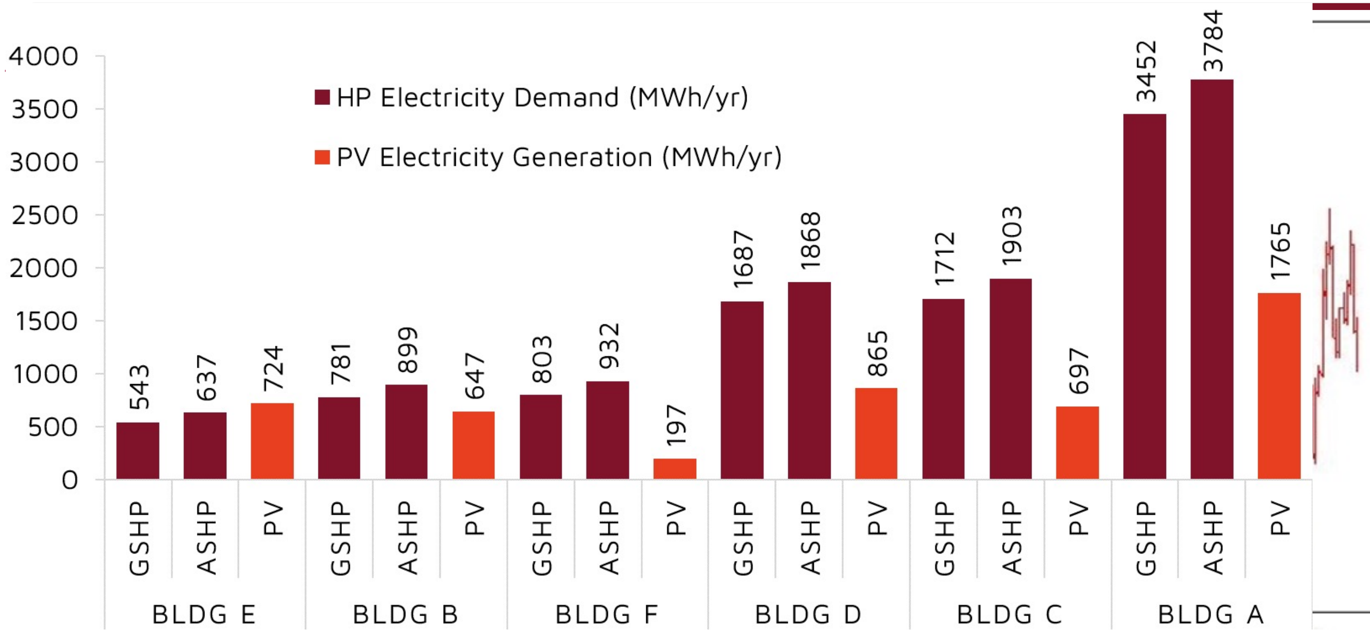
Borehole Temp °C	Outdoor Air Temp °C
-5	-30
-4.2	-25
-3.9	-15
-3	-10
-2	-5
-1.1	0
1.7	5
4.4	10
7.2	20
10	30

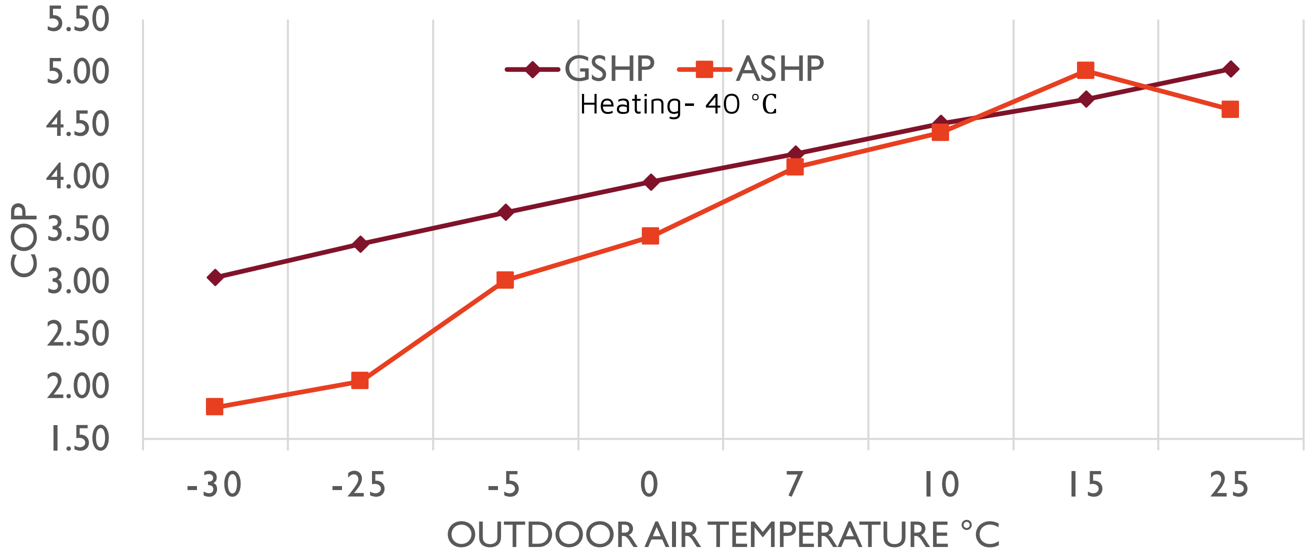


Air Source vs. Ground Source Heat Pump

Case study 1–Results & findings

- ❑Sizeable floor area vs. limited PV space
  - Foreseeable outcome: ~~Energy Positivity~~
    - ❖Exception: building E, Smallest floor area
  - PV penetration: 75-100% and as low as 30-40% in small and large buildings
- ❑ASHP vs GSPH
  - Relatively similar performance despite harsh weather
  - Lower Elec. consumption and Higher SCOP for GSHPs



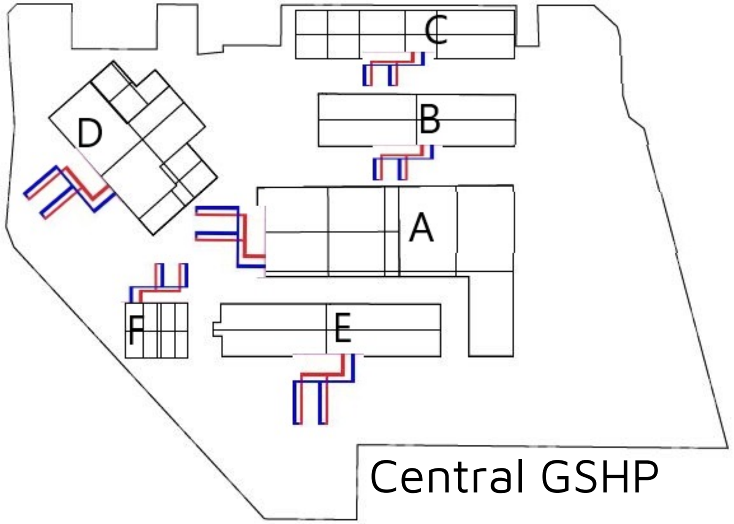


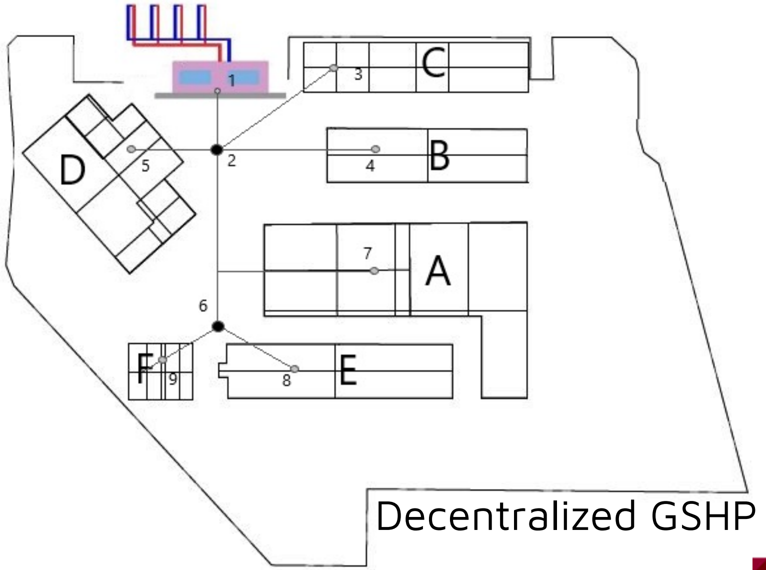
Case study 2– Dominion Bridge 2nd Objective

Decentral GSHPs

vs

Central district heating and cooling (DHC) with GSHPs





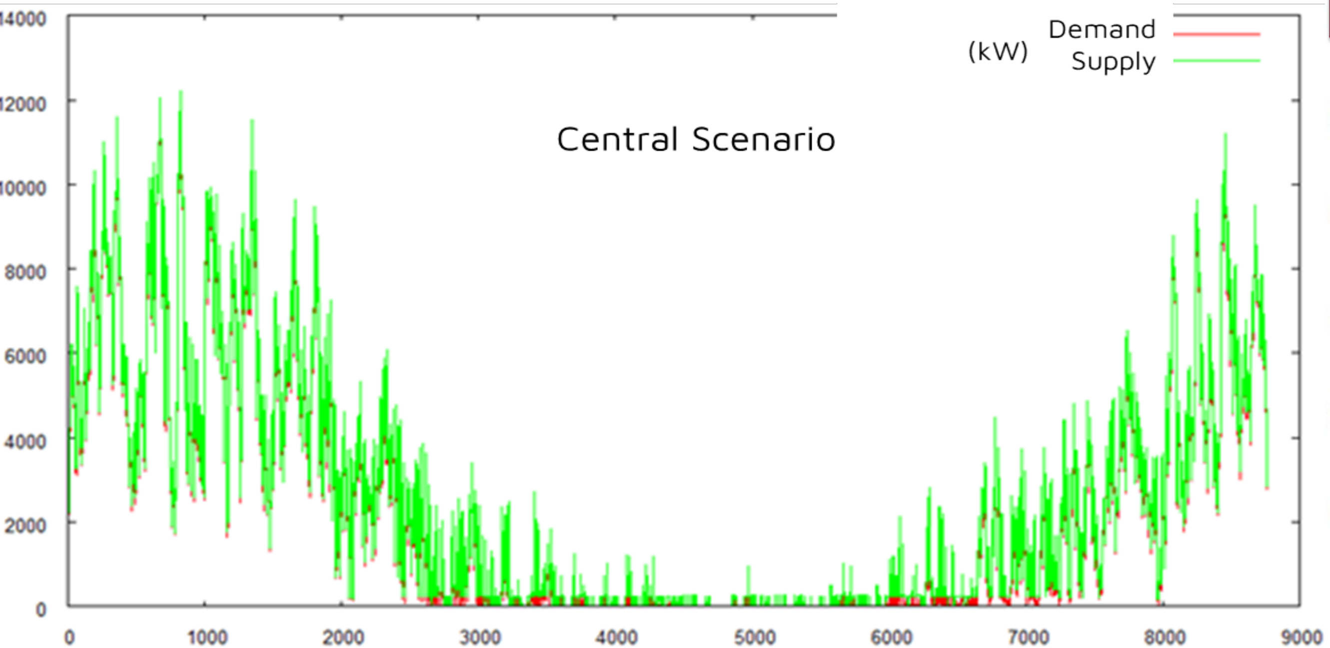
- Energy system design parameters
  - Single Stage GSHPs
  - System sizing for Peak demand and P=98%

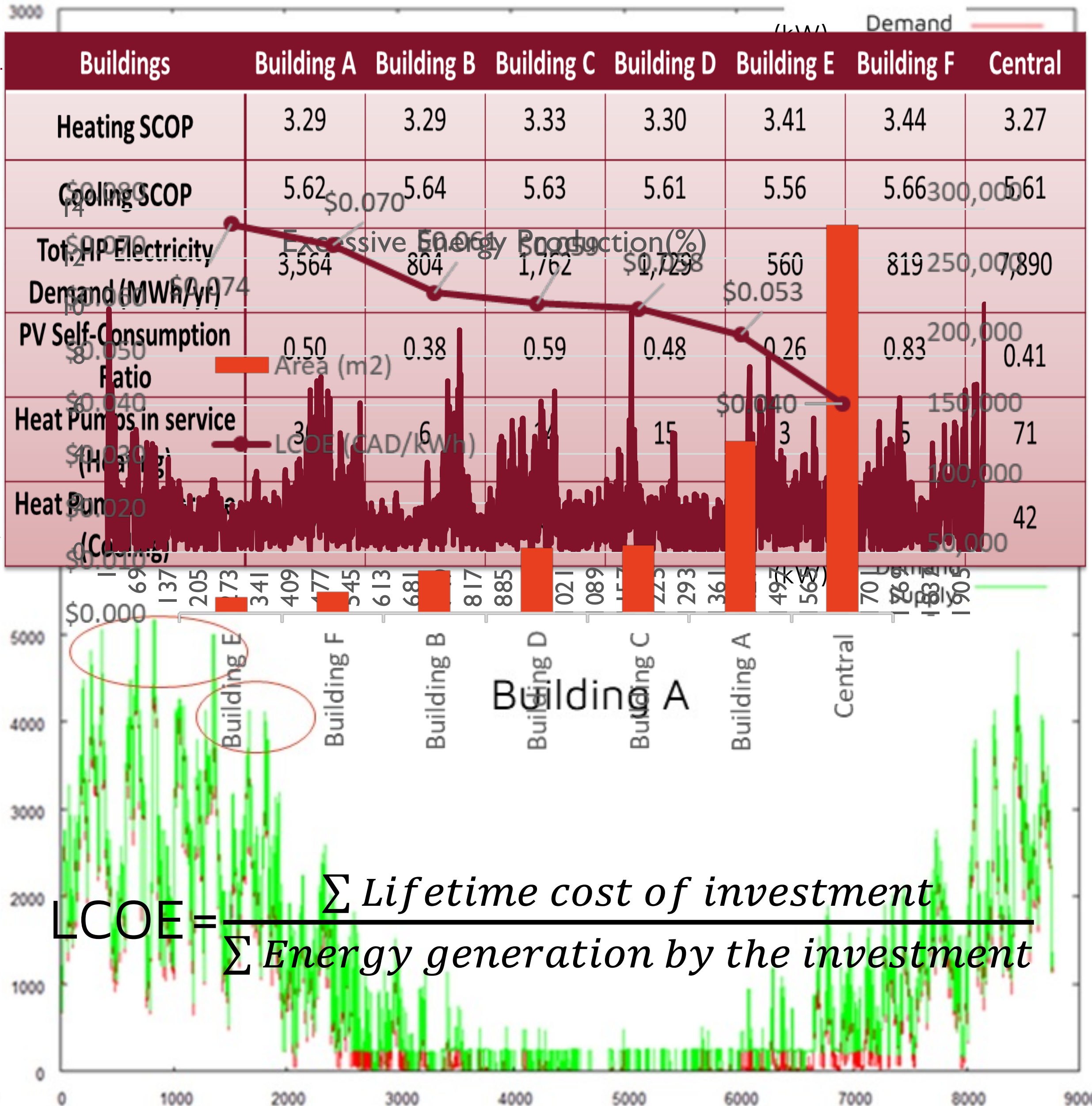
- Objectives
  - **Comparing Energy systems performance**
  - **Energy system sizing - different demand percentiles**
  - Network design – Heat loss calculation

Case study 2– Results & findings

- ❑17% less electricity consumption in Central scenario
- ❑18% lower import from the grid in Central scenario (Higher resiliency)
- ❑ 3 HPs less for DHC

Buildings	Building A	Building B	Building C	Building D	Building E	Building F	Central
Heating SCOP	3.29	3.29	3.33	3.30	3.41	3.44	3.27
Cooling SCOP	5.62	5.64	5.63	5.61	5.56	5.66	5.61
Tot. HP Electricity Demand (MWh/yr)	3,564	804	1,762	1,729	560	819	7,890
PV Self-Consumption Ratio	0.50	0.38	0.59	0.48	0.26	0.83	0.41
Heat Pumps in service (Heating)	[illegible]	6	[illegible]	15	3	5	71
Heat Pumps in service (Cooling)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	42





$$LCOE = \frac{\sum Lifetime\ cost\ of\ investment}{\sum Energy\ generation\ by\ the\ investment}$$

Case study 3

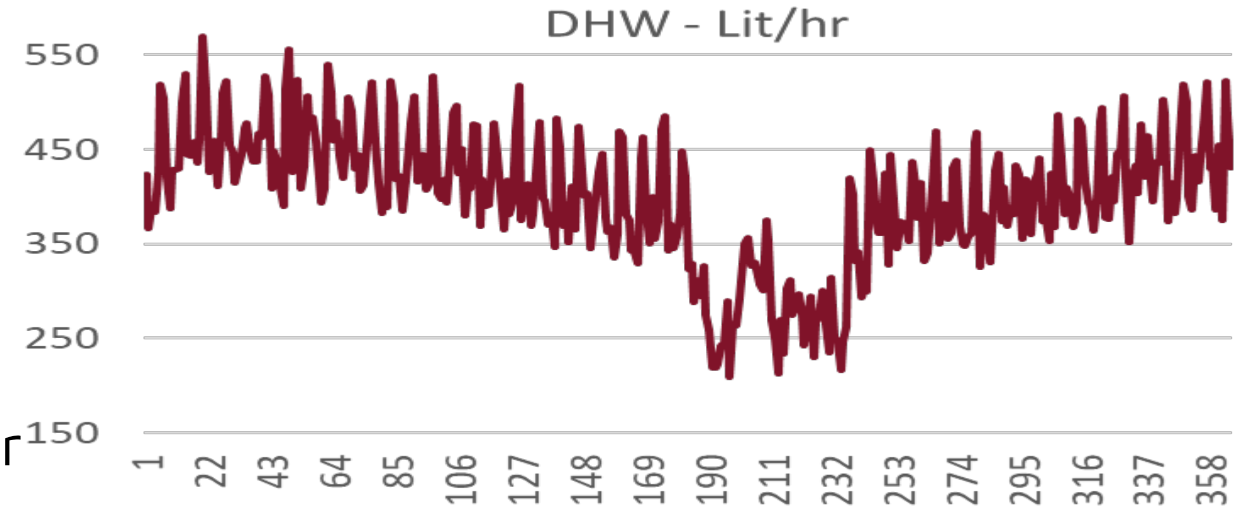
❑ Objectives

- 1st : DHW: (HP only) vs. (HP+electrical heater)
- 2nd: Finding optimum slope for PV system using Python
- 3rd : Sensitivity analysis of heating supply temperature

Number of stories-units	3-20
Total floor area (m^2)	2161
Total Roof area (m^2)	667 (23x29)
Occupant density (m^2/person)	27
DHW demand (liter/day/person)	120
DHW storage factor	1
DHW demand factor	0.3
DHW set point	40 C

Case study 3– Hot water generation-Results

- DHW usage profile generated using DHW-Calc
  - 1.5 cubic meter hot water tank
  - City water temperature of 10 C



- Higher SCOP and seasonal performance factor for HP ONLY Scenario
- Despite having heat loss, higher COP of HP makes the difference

	HP + Electric Heater	HP Only
Total EXCESSIVE ENERGY (kWh)	0	139,704
DHW HP Seasonal COP	3.22	3.55
HP Electricity Consumption (kWh/yr) (DHW)	68,558	128,113
Aux. Electric. Heater Consumption (kWh/yr)	94,116	0
Number Of Heat Pumps (DHW)	3	4
Seasonal Performance Factor	2.45	2.67

$$SPF = \frac{\sum Demand}{\sum Energy\ Consumed\ for\ Meating\ Demand} \qquad SCOP = \frac{\sum Energy\ Produced}{\sum Energy\ Consumed}$$

Case study 3– Optimum slope- Results

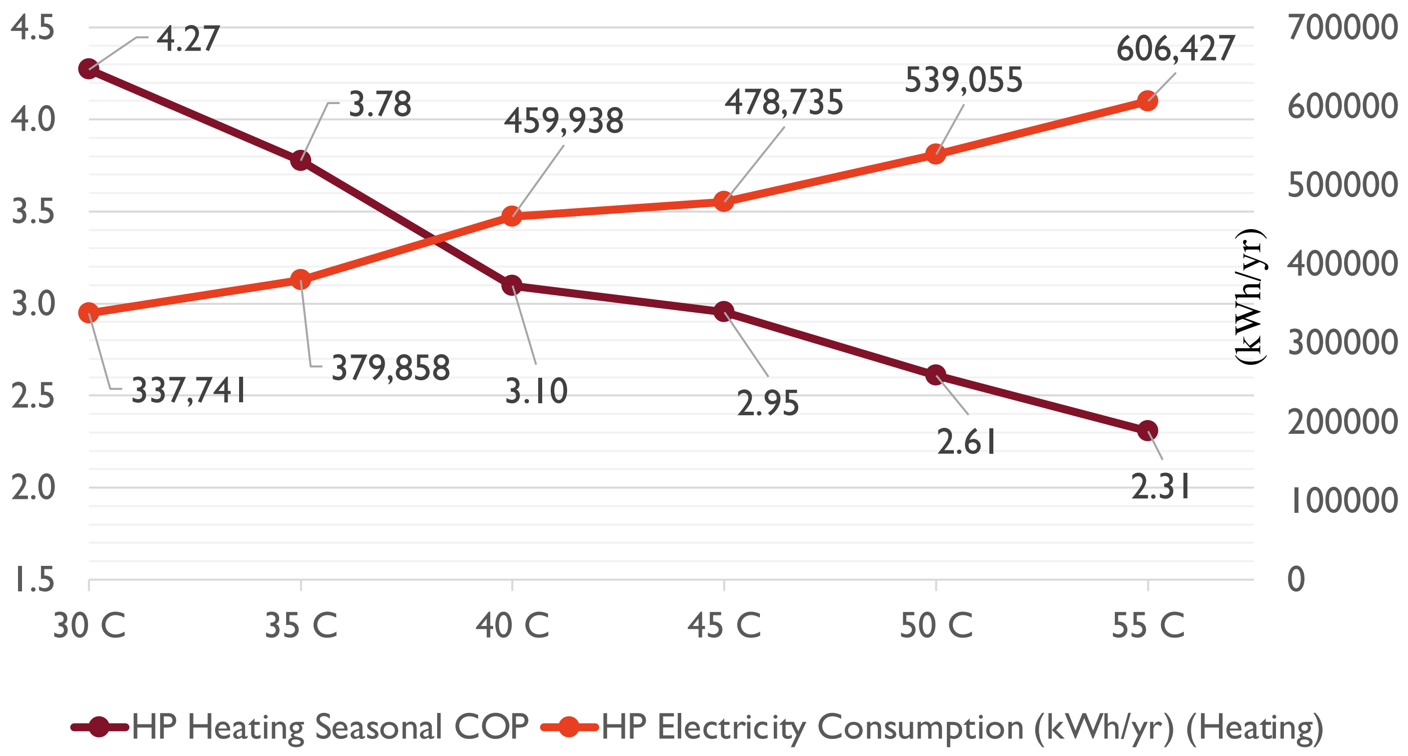
- INSEL and Python
  - Text file, PyCharm and DEAP library
- 65% roof area for PV
- Optimizing AC electricity generation
  - Considering inverter efficiency
- Result: 31 degree
  - Despite 30,34,35,37 in literature

Slope (degree)	AC Electricity Generation (kWh/yr)	Inverter Efficiency (%)	Total PV Generation (kWh/yr)
0	70802	91.50	73809
10	75641	92.41	78750
25	71808	93.14	74694
28	80336	93.26	83549
29	80386	93.22	83601
30	80405	93.21	83623
31	80431	93.18	83650
32	80424	93.12	83644
33	75905	93.00	78960
34	75859	92.98	78914
35	75801	92.94	78855
40	70652	92.92	73486
60	40737	91.14	42407
80	9706	90.54	10233
86	error	error	3125
90	error	error	error

Azimuth Angle	180
Ground reflectance	0.2
Latitude	45.5
Longitude	73.62
Nominal Power (W)	300
MPP Voltage (V)	53.76
MPP Current (A)	5.54
Efficiency (%)	17.24
Width (mm)	1072
Height (mm)	1623

Case study 3– Sensitivity Analysis- Results

- ❑Heating supply temperatures
  - 30-55 C – 5 C increment
- ❑Min, max and average increase in consumption for 5 degrees
  - 4%, 20%, and 13%
  - COP drops, average 11%



Conclusion

- UESMs contributing to existing and future energy strategies and policies
  - Gaps: transparency, flexibility, low temporal resolution, etc.
- Automated flexible workflow introduced
  - Demand calculation and energy system sizing
  - Complete solution for heating, cooling and DHW
  - Detailed model, applicable to various studies and scenarios
  - Sophisticated analyses (Optimization, Sensitivity analysis) using Python libraries

Suggestions for Future works

- ❑ Adding other energy systems (PV/T, Wind, CHP, Boiler, etc.)
- ❑ Considering inverter HPs
- ❑ Improving battery and thermal storage models

Thank You!

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References

[1]D. Kolokotsa, D. Rovas, E. Kosmatopoulos, and K. Kalaitzakis, “A roadmap towards intelligent net zero- and positive-energy buildings,” *Solar Energy*, vol. 85, no. 12. pp. 3067–3084, 2011, doi: 10.1016/j.solener.2010.09.001.

[2]J. Lizana, R. Chacartegui, … A. B.-P.-… and S. E., and undefined 2018, “Advanced low-carbon energy measures based on thermal energy storage in buildings: A review,” *Elsevier*.

[3]Canada Energy Regulator, “Canada Energy Future 2020,” p. 100, 2020.

[4]Intergovernmental Panel on Climate Change, *Climate Change 2014 Mitigation of Climate Change*. Cambridge University Press, 2014.

[5]B. Polly *et al.*, “A Guide to Energy Master Planning of High-Performance Districts and Communities,” Nov. 2020, doi: 10.2172/1734654.

[6]“Energy Technology Perspectives 2017 Catalysing Energy Technology Transformations INTERNATIONAL ENERGY AGENCY,” 2017.

[7]S. Pfenninger, A. Hawkes, and J. Keirstead, “Energy systems modeling for twenty-first century energy challenges,” *Renewable and Sustainable Energy Reviews*, vol. 33. Elsevier Ltd, pp. 74–86, 01-May-2014, doi: 10.1016/j.rser.2014.02.003.

[8]M. Yazdanie and K. Orehounig, “Advancing urban energy system planning and modeling approaches: Gaps and solutions in perspective,” *Renewable and Sustainable Energy Reviews*, vol. 137. Elsevier Ltd, 01-Mar-2021, doi: 10.1016/j.rser.2020.110607.

[9]D. Connolly, H. Lund, B. V. Mathiesen, and M. Leahy, “A review of computer tools for analysing the integration of renewable energy into various energy systems,” *Applied Energy*, vol. 87, no. 4. Elsevier Ltd, pp. 1059–1082, 01-Apr-2010, doi: 10.1016/j.apenergy.2009.09.026.

[10]S. Sinha and S. S. Chandel, “Review of software tools for hybrid renewable energy systems,” *Renewable and Sustainable Energy Reviews*, vol. 32. Pergamon, pp. 192–205, 01-Apr-2014, doi: 10.1016/j.rser.2014.01.035.

[11]H. K. Ringkjøb, P. M. Haugan, and I. M. Solbrekke, “A review of modelling tools for energy and electricity systems with large shares of variable renewables,” *Renewable and Sustainable Energy Reviews*, vol. 96. Elsevier Ltd, pp. 440–459, 01-Nov-2018, doi: 10.1016/j.rser.2018.08.002.

[12]L. M. H. Hall and A. R. Buckley, “A review of energy systems models in the UK: Prevalent usage and categorisation,” *Appl. Energy*, vol. 169, pp. 607–628, May 2016, doi: 10.1016/j.apenergy.2016.02.044.

[13]S. R. Asaee, V. I. Ugursal, and I. Beausoleil-Morrison, “Techno-economic feasibility evaluation of air to water heat pump retrofit in the Canadian housing stock,” *Appl. Therm. Eng.*, vol. 111, pp. 936–949, Jan. 2017, doi: 10.1016/j.applthermaleng.2016.09.117.

[14]A. M. Brockway and P. Delforge, “Emissions reduction potential from electric heat pumps in California homes,” *Electr. J.*, vol. 31, no. 9, pp. 44–53, Nov. 2018, doi: 10.1016/j.tej.2018.10.012.

[15]R. Renaldi, A. Kiprakis, and D. Friedrich, “An optimisation framework for thermal energy storage integration in a residential heat pump heating system,” *Appl. Energy*, vol. 186, pp. 520–529, Jan. 2017, doi: 10.1016/j.apenergy.2016.02.067.

[16]M. Jarre, M. Noussan, and M. Simonetti, “Primary energy consumption of heat pumps in high renewable share electricity mixes,” *Energy Convers. Manag.*, vol. 171, pp. 1339–1351, Sep. 2018, doi: 10.1016/j.enconman.2018.06.067.