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Supplementary information

Load-responsive control of electrochromic windows for commercial buildings: Global cooling benefits and climate-dependent energy trade-offs

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S1. Threshold sensitivity

To examine the sensitivity of fixed temperature-based EC control to the selected switching threshold, an additional T23 strategy was simulated as the EC (T23) sensitivity case using a 23 °C upper dark-state threshold. T23 used the same 21 °C lower switching threshold, EC clear and dark states, building configuration, HVAC system, thermostat schedules, weather files, and EMS implementation as T24. The only difference between T23 and T24 was the upper dark-state switching threshold.

Figure S1 compares EC (T23), EC (T24), and EC (Load) across ASHRAE climate zones. Annual EUI is shown in Fig. S1(a), while cooling electricity and heating gas are shown in Figs. S1(b) and S1(c), respectively. Changing the upper threshold from 24 °C to 23 °C affected cooling and heating differently, while the resulting changes in annual EUI remained comparatively small in many climate zones. The sensitivity analysis confirms that fixed temperature-based control also redistributes the cooling-heating balance depending on threshold selection. T24 is therefore used in the main analysis as a representative temperature-based control case rather than as a universally optimal threshold.

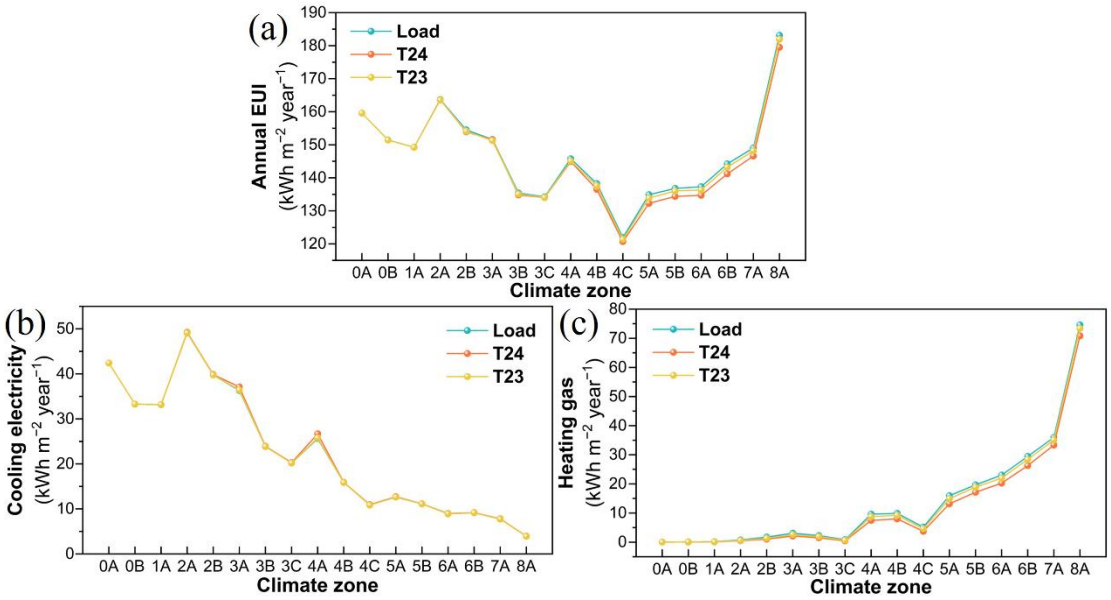


Figure S1. Sensitivity of EC performance to the temperature-based switching threshold across ASHRAE climate zones. (a) Annual EUI; (b) Cooling electricity; (c) Heating gas for EC (T23), EC (T24), and EC (Load).

S2. EMS implementation

The complete EMS implementations of the T24 and Load strategies are provided below for reproducibility. T24 uses zone mean air temperature as the sensing variable and is executed at the BeginTimestepBeforePredictor calling point. Its 21 °C clear-state and 24 °C dark-state thresholds are fixed throughout the annual simulation. The unoccupied HVAC setbacks of 15.6 °C for heating and 26.7 °C for cooling are not T24 switching thresholds. The Load strategy uses predicted sensible cooling and heating loads of the 12 perimeter zones containing the actuated EC windows. It is executed at the AfterPredictorBeforeHVACManagers calling point. The Load strategy uses only the sign of the predicted sensible load as a binary switching signal. A negative cooling-load signal selects the dark state. A positive heating-load signal selects the clear state. In all other cases, the previous state is retained. Both strategies dynamically reassign the window construction between the same predefined clear and dark EC states.

The T23 sensitivity case used the same EMS implementation as T24, except that the upper dark-state switching threshold was reduced from 24 °C to 23 °C. Therefore, a separate T23 code listing is not provided.

S2.1. T24 control

Complete EnergyPlus EMS code for the T24 strategy:

```
!-   ==========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:SENSOR ==========

EnergyManagementSystem:Sensor,
    Tbot1,                   !- Name
    Perimeter_bot_ZN_1,      !- Output:Variable or Output:Meter Index Key Name
    Zone Mean Air Temperature;  !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
    Tbot2,                   !- Name
    Perimeter_bot_ZN_2,      !- Output:Variable or Output:Meter Index Key Name
    Zone Mean Air Temperature;  !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
    Tbot3,                   !- Name
    Perimeter_bot_ZN_3,      !- Output:Variable or Output:Meter Index Key Name
    Zone Mean Air Temperature;  !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
    Tbot4,                   !- Name
    Perimeter_bot_ZN_4,      !- Output:Variable or Output:Meter Index Key Name
    Zone Mean Air Temperature;  !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
    Tmid1,                   !- Name
```

```
    Perimeter_mid_ZN_1,           !- Output:Variable or Output:Meter Index Key Name
    Zone Mean Air Temperature;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Tmid2,                        !- Name
    Perimeter_mid_ZN_2,           !- Output:Variable or Output:Meter Index Key Name
    Zone Mean Air Temperature;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Tmid3,                        !- Name
    Perimeter_mid_ZN_3,           !- Output:Variable or Output:Meter Index Key Name
    Zone Mean Air Temperature;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Tmid4,                        !- Name
    Perimeter_mid_ZN_4,           !- Output:Variable or Output:Meter Index Key Name
    Zone Mean Air Temperature;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Ttop1,                        !- Name
    Perimeter_top_ZN_1,           !- Output:Variable or Output:Meter Index Key Name
    Zone Mean Air Temperature;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Ttop2,                        !- Name
    Perimeter_top_ZN_2,           !- Output:Variable or Output:Meter Index Key Name
    Zone Mean Air Temperature;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Ttop3,                        !- Name
    Perimeter_top_ZN_3,           !- Output:Variable or Output:Meter Index Key Name
    Zone Mean Air Temperature;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Ttop4,                        !- Name
    Perimeter_top_ZN_4,           !- Output:Variable or Output:Meter Index Key Name
    Zone Mean Air Temperature;    !- Output:Variable or Output:Meter Name

!-   ==========   ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:ACTUATOR ==========
EnergyManagementSystem:Actuator,
    ActBotS,                      !- Name
    Perimeter_bot_ZN_1_Wall_South_Window,    !- Actuated Component Unique Name
    Surface,                      !- Actuated Component Type
    Construction State;           !- Actuated Component Control Type
EnergyManagementSystem:Actuator,
    ActBotE,                      !- Name
```

```
    Perimeter_bot_ZN_2_Wall_East_Window,    !- Actuated Component Unique Name
    Surface,                                !- Actuated Component Type
    Construction State;                     !- Actuated Component Control Type

EnergyManagementSystem:Actuator,
    ActBotN,                                !- Name
    Perimeter_bot_ZN_3_Wall_North_Window,    !- Actuated Component Unique Name
    Surface,                                !- Actuated Component Type
    Construction State;                     !- Actuated Component Control Type

EnergyManagementSystem:Actuator,
    ActBotW,                                !- Name
    Perimeter_bot_ZN_4_Wall_West_Window,    !- Actuated Component Unique Name
    Surface,                                !- Actuated Component Type
    Construction State;                     !- Actuated Component Control Type

EnergyManagementSystem:Actuator,
    ActMidS,                                !- Name
    Perimeter_mid_ZN_1_Wall_South_Window,    !- Actuated Component Unique Name
    Surface,                                !- Actuated Component Type
    Construction State;                     !- Actuated Component Control Type

EnergyManagementSystem:Actuator,
    ActMidE,                                !- Name
    Perimeter_mid_ZN_2_Wall_East_Window,    !- Actuated Component Unique Name
    Surface,                                !- Actuated Component Type
    Construction State;                     !- Actuated Component Control Type

EnergyManagementSystem:Actuator,
    ActMidN,                                !- Name
    Perimeter_mid_ZN_3_Wall_North_Window,    !- Actuated Component Unique Name
    Surface,                                !- Actuated Component Type
    Construction State;                     !- Actuated Component Control Type

EnergyManagementSystem:Actuator,
    ActMidW,                                !- Name
    Perimeter_mid_ZN_4_Wall_West_Window,    !- Actuated Component Unique Name
    Surface,                                !- Actuated Component Type
    Construction State;                     !- Actuated Component Control Type

EnergyManagementSystem:Actuator,
    ActTopS,                                !- Name
    Perimeter_top_ZN_1_Wall_South_Window,    !- Actuated Component Unique Name
    Surface,                                !- Actuated Component Type
    Construction State;                     !- Actuated Component Control Type

EnergyManagementSystem:Actuator,
```

```
    ActTopE,                        !- Name
    Perimeter_top_ZN_2_Wall_East_Window,    !- Actuated Component Unique Name
    Surface,                        !- Actuated Component Type
    Construction State;         !- Actuated Component Control Type
EnergyManagementSystem:Actuator,
    ActTopN,                        !- Name
    Perimeter_top_ZN_3_Wall_North_Window,    !- Actuated Component Unique Name
    Surface,                        !- Actuated Component Type
    Construction State;         !- Actuated Component Control Type
EnergyManagementSystem:Actuator,
    ActTopW,                        !- Name
    Perimeter_top_ZN_4_Wall_West_Window,    !- Actuated Component Unique Name
    Surface,                        !- Actuated Component Type
    Construction State;         !- Actuated Component Control Type

!-   ==========   ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAMCALLINGMANAGER ==========

EnergyManagementSystem:ProgramCallingManager,
    SmartWindowManager,         !- Name
    BeginTimestepBeforePredictor,    !- EnergyPlus Model Calling Point
    SmartWindowLogic;           !- Program Name 1

!-   ==========   ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAM ==========

EnergyManagementSystem:Program,
    SmartWindowLogic,           !- Name
    IF Tbot1 > 24.0,            !- Program Line 1
    SET ActBotS = DarkID,       !- Program Line 2
    ELSEIF Tbot1 < 21.0,        !- A4
    SET ActBotS = ClearID,      !- A5
    ENDIF,                      !- A6
    IF Tbot2 > 24.0,            !- A7
    SET ActBotE = DarkID,       !- A8
    ELSEIF Tbot2 < 21.0,        !- A9
    SET ActBotE = ClearID,      !- A10
    ENDIF,                      !- A11
    IF Tbot3 > 24.0,            !- A12
    SET ActBotN = DarkID,       !- A13
    ELSEIF Tbot3 < 21.0,        !- A14
    SET ActBotN = ClearID,      !- A15
```

```
ENDIF,                          !- A16
IF Tbot4 > 24.0,                !- A17
SET ActBotW = DarkID,           !- A18
ELSEIF Tbot4 < 21.0,            !- A19
SET ActBotW = ClearID,          !- A20
ENDIF,                          !- A21
IF Tmid1 > 24.0,                !- A22
SET ActMidS = DarkID,           !- A23
ELSEIF Tmid1 < 21.0,            !- A24
SET ActMidS = ClearID,          !- A25
ENDIF,                          !- A26
IF Tmid2 > 24.0,                !- A27
SET ActMidE = DarkID,           !- A28
ELSEIF Tmid2 < 21.0,            !- A29
SET ActMidE = ClearID,          !- A30
ENDIF,                          !- A31
IF Tmid3 > 24.0,                !- A32
SET ActMidN = DarkID,           !- A33
ELSEIF Tmid3 < 21.0,            !- A34
SET ActMidN = ClearID,          !- A35
ENDIF,                          !- A36
IF Tmid4 > 24.0,                !- A37
SET ActMidW = DarkID,           !- A38
ELSEIF Tmid4 < 21.0,            !- A39
SET ActMidW = ClearID,          !- A40
ENDIF,                          !- A41
IF Ttop1 > 24.0,                !- A42
SET ActTopS = DarkID,           !- A43
ELSEIF Ttop1 < 21.0,            !- A44
SET ActTopS = ClearID,          !- A45
ENDIF,                          !- A46
IF Ttop2 > 24.0,                !- A47
SET ActTopE = DarkID,           !- A48
ELSEIF Ttop2 < 21.0,            !- A49
SET ActTopE = ClearID,          !- A50
ENDIF,                          !- A51
IF Ttop3 > 24.0,                !- A52
SET ActTopN = DarkID,           !- A53
ELSEIF Ttop3 < 21.0,            !- A54
```

```
    SET ActTopN = ClearID,      !- A55
    ENDIF,                      !- A56
    IF Ttop4 > 24.0,            !- A57
    SET ActTopW = DarkID,       !- A58
    ELSEIF Ttop4 < 21.0,        !- A59
    SET ActTopW = ClearID,      !- A60
    ENDIF;                      !- A61

!- ========== ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:CONSTRUCTIONINDEXVARIABLE ==========

EnergyManagementSystem:ConstructionIndexVariable,
    DarkID,                     !- Name
    DarkState;                  !- Construction Object Name

EnergyManagementSystem:ConstructionIndexVariable,
    ClearID,                    !- Name
    ClearState;                 !- Construction Object Name
```

S2.2. Load control

The monitored EnergyPlus outputs were Zone Predicted Sensible Load to Cooling Setpoint Heat Transfer Rate and Zone Predicted Sensible Load to Heating Setpoint Heat Transfer Rate. Complete EnergyPlus EMS code for the Load strategy:

```
!- ========== ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:SENSOR ==========

! --- Bottom Floor Energy Sensors ---

EnergyManagementSystem:Sensor,
    Qbot1_C,                    !- Name
    Perimeter_bot_ZN_1,         !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Cooling Setpoint Heat Transfer Rate;   !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
    Qbot1_H,                    !- Name
    Perimeter_bot_ZN_1,         !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Heating Setpoint Heat Transfer Rate;   !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
    Qbot2_C,                    !- Name
    Perimeter_bot_ZN_2,         !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Cooling Setpoint Heat Transfer Rate;   !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
    Qbot2_H,                    !- Name
    Perimeter_bot_ZN_2,         !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Heating Setpoint Heat Transfer Rate;   !- Output:Variable or Output:Meter Name
```

```
EnergyManagementSystem:Sensor,
    Qbot3_C,                  !- Name
    Perimeter_bot_ZN_3,       !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Cooling Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qbot3_H,                  !- Name
    Perimeter_bot_ZN_3,       !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Heating Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qbot4_C,                  !- Name
    Perimeter_bot_ZN_4,       !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Cooling Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qbot4_H,                  !- Name
    Perimeter_bot_ZN_4,       !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Heating Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
! --- Middle Floor Energy Sensors ---
EnergyManagementSystem:Sensor,
    Qmid1_C,                  !- Name
    Perimeter_mid_ZN_1,       !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Cooling Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qmid1_H,                  !- Name
    Perimeter_mid_ZN_1,       !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Heating Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qmid2_C,                  !- Name
    Perimeter_mid_ZN_2,       !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Cooling Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qmid2_H,                  !- Name
    Perimeter_mid_ZN_2,       !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Heating Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qmid3_C,                  !- Name
    Perimeter_mid_ZN_3,       !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Cooling Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qmid3_H,                  !- Name
```

```
    Perimeter_mid_ZN_3,          !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Heating Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qmid4_C,                     !- Name
    Perimeter_mid_ZN_4,          !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Cooling Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qmid4_H,                     !- Name
    Perimeter_mid_ZN_4,          !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Heating Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
! --- Top Floor Energy Sensors ---
EnergyManagementSystem:Sensor,
    Qtop1_C,                     !- Name
    Perimeter_top_ZN_1,          !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Cooling Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qtop1_H,                     !- Name
    Perimeter_top_ZN_1,          !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Heating Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qtop2_C,                     !- Name
    Perimeter_top_ZN_2,          !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Cooling Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qtop2_H,                     !- Name
    Perimeter_top_ZN_2,          !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Heating Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qtop3_C,                     !- Name
    Perimeter_top_ZN_3,          !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Cooling Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qtop3_H,                     !- Name
    Perimeter_top_ZN_3,          !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Heating Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Qtop4_C,                     !- Name
    Perimeter_top_ZN_4,          !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Cooling Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name
```

```
EnergyManagementSystem:Sensor,
    Qtop4_H,                    !- Name
    Perimeter_top_ZN_4,         !- Output:Variable or Output:Meter Index Key Name
    Zone Predicted Sensible Load to Heating Setpoint Heat Transfer Rate;    !- Output:Variable or Output:Meter Name

!-   ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:ACTUATOR ===========
EnergyManagementSystem:Actuator,
    ActBotS,                    !- Name
    Perimeter_bot_ZN_1_Wall_South_Window,    !- Actuated Component Unique Name
    Surface,                    !- Actuated Component Type
    Construction State;         !- Actuated Component Control Type
EnergyManagementSystem:Actuator,
    ActBotE,                    !- Name
    Perimeter_bot_ZN_2_Wall_East_Window,    !- Actuated Component Unique Name
    Surface,                    !- Actuated Component Type
    Construction State;         !- Actuated Component Control Type
EnergyManagementSystem:Actuator,
    ActBotN,                    !- Name
    Perimeter_bot_ZN_3_Wall_North_Window,    !- Actuated Component Unique Name
    Surface,                    !- Actuated Component Type
    Construction State;         !- Actuated Component Control Type
EnergyManagementSystem:Actuator,
    ActBotW,                    !- Name
    Perimeter_bot_ZN_4_Wall_West_Window,    !- Actuated Component Unique Name
    Surface,                    !- Actuated Component Type
    Construction State;         !- Actuated Component Control Type
EnergyManagementSystem:Actuator,
    ActMidS,                    !- Name
    Perimeter_mid_ZN_1_Wall_South_Window,    !- Actuated Component Unique Name
    Surface,                    !- Actuated Component Type
    Construction State;         !- Actuated Component Control Type
EnergyManagementSystem:Actuator,
    ActMidE,                    !- Name
    Perimeter_mid_ZN_2_Wall_East_Window,    !- Actuated Component Unique Name
    Surface,                    !- Actuated Component Type
    Construction State;         !- Actuated Component Control Type
EnergyManagementSystem:Actuator,
    ActMidN,                    !- Name
    Perimeter_mid_ZN_3_Wall_North_Window,    !- Actuated Component Unique Name
```

```
    Surface,                  !- Actuated Component Type
    Construction State;       !- Actuated Component Control Type
EnergyManagementSystem:Actuator,
    ActMidW,                  !- Name
    Perimeter_mid_ZN_4_Wall_West_Window,  !- Actuated Component Unique Name
    Surface,                  !- Actuated Component Type
    Construction State;       !- Actuated Component Control Type
EnergyManagementSystem:Actuator,
    ActTopS,                  !- Name
    Perimeter_top_ZN_1_Wall_South_Window,  !- Actuated Component Unique Name
    Surface,                  !- Actuated Component Type
    Construction State;       !- Actuated Component Control Type
EnergyManagementSystem:Actuator,
    ActTopE,                  !- Name
    Perimeter_top_ZN_2_Wall_East_Window,  !- Actuated Component Unique Name
    Surface,                  !- Actuated Component Type
    Construction State;       !- Actuated Component Control Type
EnergyManagementSystem:Actuator,
    ActTopN,                  !- Name
    Perimeter_top_ZN_3_Wall_North_Window,  !- Actuated Component Unique Name
    Surface,                  !- Actuated Component Type
    Construction State;       !- Actuated Component Control Type
EnergyManagementSystem:Actuator,
    ActTopW,                  !- Name
    Perimeter_top_ZN_4_Wall_West_Window,  !- Actuated Component Unique Name
    Surface,                  !- Actuated Component Type
    Construction State;       !- Actuated Component Control Type

!-   ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAMCALLINGMANAGER
==========

EnergyManagementSystem:ProgramCallingManager,
    SmartWindowManager,       !- Name
    AfterPredictorBeforeHVACManagers,  !- EnergyPlus Model Calling Point
    SmartWindowLogic;         !- Program Name 1

!-   ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAM ===========

! --- Bottom Floor Logic ---

! --- Middle Floor Logic ---

! --- Top Floor Logic ---
```

```
EnergyManagementSystem:Program,
    SmartWindowLogic,              !- Name
    IF Qbot1_C < 0,                !- Program Line 1
    SET ActBotS = DarkID,          !- Program Line 2
    ELSEIF Qbot1_H > 0,            !- A4
    SET ActBotS = ClearID,         !- A5
    ENDIF,                         !- A6
    IF Qbot2_C < 0,                !- A7
    SET ActBotE = DarkID,          !- A8
    ELSEIF Qbot2_H > 0,            !- A9
    SET ActBotE = ClearID,         !- A10
    ENDIF,                         !- A11
    IF Qbot3_C < 0,                !- A12
    SET ActBotN = DarkID,          !- A13
    ELSEIF Qbot3_H > 0,            !- A14
    SET ActBotN = ClearID,         !- A15
    ENDIF,                         !- A16
    IF Qbot4_C < 0,                !- A17
    SET ActBotW = DarkID,          !- A18
    ELSEIF Qbot4_H > 0,            !- A19
    SET ActBotW = ClearID,         !- A20
    ENDIF,                         !- A21
    IF Qmid1_C < 0,                !- A22
    SET ActMidS = DarkID,          !- A23
    ELSEIF Qmid1_H > 0,            !- A24
    SET ActMidS = ClearID,         !- A25
    ENDIF,                         !- A26
    IF Qmid2_C < 0,                !- A27
    SET ActMidE = DarkID,          !- A28
    ELSEIF Qmid2_H > 0,            !- A29
    SET ActMidE = ClearID,         !- A30
    ENDIF,                         !- A31
    IF Qmid3_C < 0,                !- A32
    SET ActMidN = DarkID,          !- A33
    ELSEIF Qmid3_H > 0,            !- A34
    SET ActMidN = ClearID,         !- A35
    ENDIF,                         !- A36
    IF Qmid4_C < 0,                !- A37
    SET ActMidW = DarkID,          !- A38
```

```
      ELSEIF Qmid4_H > 0,          !- A39
      SET ActMidW = ClearID,     !- A40
      ENDIF,                       !- A41
      IF Qtop1_C < 0,              !- A42
      SET ActTopS = DarkID,      !- A43
      ELSEIF Qtop1_H > 0,          !- A44
      SET ActTopS = ClearID,     !- A45
      ENDIF,                       !- A46
      IF Qtop2_C < 0,              !- A47
      SET ActTopE = DarkID,      !- A48
      ELSEIF Qtop2_H > 0,          !- A49
      SET ActTopE = ClearID,     !- A50
      ENDIF,                       !- A51
      IF Qtop3_C < 0,              !- A52
      SET ActTopN = DarkID,      !- A53
      ELSEIF Qtop3_H > 0,          !- A54
      SET ActTopN = ClearID,     !- A55
      ENDIF,                       !- A56
      IF Qtop4_C < 0,              !- A57
      SET ActTopW = DarkID,      !- A58
      ELSEIF Qtop4_H > 0,          !- A59
      SET ActTopW = ClearID,     !- A60
      ENDIF;                       !- A61

!-                    ==========  ALL  OBJECTS  IN  CLASS:
ENERGYMANAGEMENTSYSTEM:CONSTRUCTIONINDEXVARIABLE ==========
EnergyManagementSystem:ConstructionIndexVariable,
      DarkID,                      !- Name
      DarkState;                   !- Construction Object Name
EnergyManagementSystem:ConstructionIndexVariable,
      ClearID,                     !- Name
      ClearState;                  !- Construction Object Name
```

S3. Model configuration, data processing, and reporting definitions

S3.1. Weather-file sampling and annual aggregation

Supplementary Data File 1 provides the record-level metadata for the 384 EPW records used in this study, including the EPW record identifier, city, country, latitude, longitude, and assigned climate-zone category. The EPW data source, ASHRAE climate-zone classification, and stratified selection procedure are described in Section 2.5 of the main manuscript.

For annual and global summaries, monthly results from January to December were first summed for each EPW record. The arithmetic mean was then calculated within each of the 17 climate-zone categories. The 17-category means were subsequently averaged with equal weight to obtain the annual and global summaries. Thus, the annual and global values were not calculated as a direct arithmetic mean of all 384 EPW records.

For the climate-zone statistics presented in Fig. 3, the EPW-record-level EC (T24) − EC (Load) differences were grouped by detailed climate-zone category. The arithmetic mean and two-sided 95 % confidence interval for each category were calculated as $\bar{x} \pm t_{0.975,n-1} \frac{s}{\sqrt{n}}$, where n is the number of EPW records in the corresponding category, s is the sample standard deviation of the record-level differences, and $t_{0.975,n-1}$ is the corresponding critical value of the Student's t distribution with $n-1$ degrees of freedom. The category-specific sample sizes are reported in Table S4 and Supplementary Data File 1. Because the EPW records were selected to provide stratified climate-zone and geographic coverage rather than as random independent samples, the intervals are not interpreted as population-level uncertainty.

S3.2. Principal simulation settings

Table S1. Principal model settings retained across the fixed Low-E reference, EC (Load), and EC (T24) simulations.

Item	Setting
Reference building	DOE Commercial Reference Building Large Office; ASHRAE Standard 90.1-2004 prototype.
Simulation engine	EnergyPlus version 9.1; six zone timesteps per hour (nominal 10-min zone timestep).
Simulation period and warm-up	Full annual simulation for each EPW record; EnergyPlus default warm-up settings retained (minimum 6 and maximum 25 days).
Building geometry	12 office floors plus basement; total floor area 46,320 m^2; window-to-wall ratio 38 %; original DOE thermal zoning retained.
HVAC and schedules	Original DOE reference-building multi-zone variable air volume system, sizing, internal loads, ventilation, infiltration, and schedules were retained in all cases.
Thermostat schedules	Occupied heating/cooling setpoints: 21.0/24.0 °C; unoccupied HVAC setbacks: 15.6/26.7 °C.
Envelope and shading	Original DOE constructions retained; no detached shading devices, natural ventilation, or daylight-responsive lighting controls.
Case-specific changes	The fixed Low-E reference differed from the EC cases in its window-material representation. EC (Load) and EC (T24) used the same EC states and differed only in EMS control logic. All other model inputs were retained.

S3.3. Window representations and comparison basis

Table S2. Window properties and EnergyPlus representations used in the simulations.

Window case	EnergyPlus representation	U-factor (W m^{-2} K^{-1})	SHGC	T_{vis}	EMS switching
EC clear	WindowMaterial:SimpleGlazingSystem	1.90	0.65	0.68	Yes
EC dark	WindowMaterial:SimpleGlazingSystem	1.90	0.08	0.10	Yes
Low-E reference	WindowMaterial:Glazing	3.43748 (EnergyPlus output)	Not directly specified or reported	0.85	No

Low-E glazing-layer inputs: thickness = 0.006 m; solar transmittance = 0.63; solar reflectance, front/back = 0.19/0.22; T_{vis} = 0.85; visible reflectance, front/back = 0.056/0.079; infrared transmittance = 0; infrared emissivity, front/back = 0.84/0.10; conductivity = 0.90 W m^{-1} K^{-1}.

The fixed Low-E reference was represented in EnergyPlus as a single 6-mm glazing layer using the WindowMaterial:Glazing object. The optical properties were adopted from the column labeled “Commercial low-E glass” in Supporting Information Table S5 of Wang et al. [23]. The EnergyPlus output reported a U-factor of 3.43748 W m^{-2} K^{-1} for the modeled construction. A whole-window SHGC was not directly specified in the source data or reported in the available EnergyPlus output and was therefore not inferred from the glazing-layer properties. The Low-E reference remained fixed throughout the simulations without active EMS switching.

S3.4. EUI and carbon-equivalent definitions

Whole-building EUI was calculated as (Electricity:Facility + Heating:Gas), converted to kWh where necessary, and divided by 46,320 m^2. Other electricity was calculated as Electricity:Facility − (Cooling:Electricity + Fans:Electricity + InteriorLights:Electricity + InteriorEquipment:Electricity). Because Other is a residual within Electricity:Facility, it was not added separately to EUI. Values shown in the manuscript were calculated from unrounded source values and conventionally rounded to two decimal places.

Carbon-equivalent calculations used the EnergyPlus environmental-impact and fuel-factor settings associated with the DOE reference-building model. The reported output was Carbon Equivalent:Facility. The carbon-equivalent conversion factors were 0.2727 kg C kg^{-1} CO_2, 6.2727 kg C kg^{-1} CH_4, and 80.7272 kg C kg^{-1} N_2O. The fuel-specific emission factors listed in Table S3 are reported in g MJ^{-1}, consistent with the units specified in the original EnergyPlus FuelFactors objects. Electricity emission factors were specific to the corresponding DOE climate-zone reference model and were not customized to the country or electricity grid of each EPW location. Natural-gas emission factors were uniform across the corresponding reference-building models. The fixed Low-E reference, EC (Load), and EC (T24) cases retained the same factor definitions for each corresponding climate-zone model. The factors were inherited from the original DOE reference-building Input Data Files (IDFs) and were not modified by the EMS or glazing definitions.

Table S3. Fuel-specific emission factors inherited from the DOE reference-building IDFs and used for the EnergyPlus Carbon Equivalent:Facility output.

Climate zone	Electricity CO_2 (g MJ^{-1})	Electricity CH_4 (g MJ^{-1})	Electricity N_2O (g MJ^{-1})	NaturalGas CO_2 (g MJ^{-1})	NaturalGas CH_4 (g MJ^{-1})	NaturalGas N_2O (g MJ^{-1})
0A	176.4	0.4722	0.003306	52.1	0.00106	0.00106
0B	176.4	0.4722	0.003306	52.1	0.00106	0.00106
1A	176.4	0.4722	0.003306	52.1	0.00106	0.00106
2A	232.5	0.7306	0.0055	52.1	0.00106	0.00106
2B	197.2	0.5056	0.004667	52.1	0.00106	0.00106
3A	194.2	0.3722	0.004722	52.1	0.00106	0.00106
3B	86.67	0.4528	0.001756	52.1	0.00106	0.00106
3C	86.67	0.4528	0.001756	52.1	0.00106	0.00106
4A	168.1	0.3167	0.003528	52.1	0.00106	0.00106
4B	264.4	0.625	0.00675	52.1	0.00106	0.00106
4C	48.06	0.1422	0.1319	52.1	0.00106	0.00106
5A	341.7	0.7472	0.008028	52.1	0.00106	0.00106
5B	264.4	0.625	0.00675	52.1	0.00106	0.00106
6A	219.2	0.4806	0.006306	52.1	0.00106	0.00106
6B	236.1	0.525	0.006667	52.1	0.00106	0.00106
7A	219.2	0.4806	0.006306	52.1	0.00106	0.00106
8A	195.8	0.7917	0.003833	52.1	0.00106	0.00106

The electricity and NaturalGas columns report fuel-specific pollutant emission factors in g MJ^{-1}. The carbon-equivalent conversion factors applied by EnergyPlus were 0.2727 kg C kg^{-1} CO_2, 6.2727 kg C kg^{-1} CH_4, and 80.7272 kg C kg^{-1} N_2O. Electricity factors were inherited from the corresponding DOE climate-zone reference-building IDF and were not location-specific electricity-grid factors. NaturalGas factors were 52.1 g MJ^{-1} for CO_2, 0.001060 g MJ^{-1} for CH_4, and 0.001060 g MJ^{-1} for N_2O. The 0A and 0B cases used the factor definitions of the 1A reference-building IDF.

S3.5. Figure 2 processing workflow

Figure 2 was prepared from post-processed output data generated by EnergyPlus version 9.1. For each of the 17 ASHRAE Standard 169-2020 climate-zone categories, one climate-zone mean difference was calculated for each of the four plotted metrics. All values in Supporting Information Table S4 represent the difference EC (T24) − EC (Load). Weather-station coordinates were obtained from the LOCATION records of the corresponding EPW files. For each panel, each climate-zone mean was matched to the numerical range shown by the corresponding color scale. The associated hexadecimal color was applied to each corresponding climate-zone layer on the world map. This step was used only for geographic visualization and figure composition and did not generate or modify the underlying numerical results.

Table S4. Climate-zone-averaged annual differences between EC (T24) and EC (Load) across 384 EPW records.

Climate zone	Facility electricity (MWh)	Cooling electricity (MWh)	Heating gas (MWh)	Carbon equivalent (t C)	EPW records
0A	0.493196288	0.289834033	-1.089626175	0.035049	32
0B	1.317631325	0.723739751	-2.254738841	0.127425	23
1A	2.366077579	1.454968261	-3.774483756	0.242941	25
2A	8.977343603	7.027961354	-13.05893989	1.53927	21
2B	7.256222954	4.228747784	-34.62742871	-0.28514	23
3A	43.40260368	36.27407555	-46.21159922	6.320115	22
3B	7.884729934	4.034467604	-35.21695236	-1.05742	21
3C	8.009611808	4.125823637	-18.72020181	-0.19621	22
4A	58.49109464	48.49682169	-99.27192898	5.020412	21
4B	5.563993369	1.917012494	-82.5009043	-2.71344	21
4C	9.598525232	4.435702046	-65.87929524	-2.53981	22
5A	9.10960963	4.377332609	-129.9450686	-3.45871	21
5B	5.877936062	1.785798019	-117.7178037	-4.43986	23
6A	8.159709464	3.574257776	-128.1514991	-4.73777	21
6B	5.513433034	1.653040545	-146.0387816	-6.16406	22
7A	7.523946332	3.058167912	-121.0517837	-4.51717	22
8A	6.227404463	1.678409998	-174.6736155	-7.67685	22

Values in the Facility electricity, Cooling electricity, Heating gas, and Carbon equivalent columns are calculated as EC (T24) − EC (Load). Positive values indicate lower energy use or carbon-equivalent output under EC (Load), whereas negative values indicate higher values under EC (Load). Energy values are reported in MWh, and carbon-equivalent values are reported in t C. The EPW records column indicates the number of weather-file records included in each climate-zone mean and is not a difference.

S3.6. Positioning of the Load strategy

Table S5. Methodological positioning of the Load strategy relative to other rule-based load control, predictive control, and MPC approaches.

Feature	Present Load strategy	Other rule-based load control	General predictive control	MPC
Control formulation or role	Binary benchmark for isolating switching-signal effects	Preset rules based on current load	Control informed by predicted outcomes or conditions	Receding-horizon optimization
Primary input	Sign of the current-timestep EnergyPlus-predicted sensible heating/cooling load	Current measured or calculated load	Current conditions together with predicted loads, performance, or environmental variables	Estimated current states and forecast disturbances
Load magnitude	Not used	May be used	May be used	May be represented in the prediction model or objective function, but is not necessarily a direct input
Direct temperature, solar, occupancy, daylight, or carbon inputs	Not used directly; their effects may be reflected indirectly in the predicted load	Implementation dependent	May be used	May be included as states, constraints, disturbances, or forecasts
Objective function	Not included	No explicit optimization objective	Optional	Core component
Use of future information	No	Typically no	Method dependent; may use real-time predictions or future forecasts	Yes; future states and disturbances are predicted over a finite horizon
Prediction horizon	None	None	Method dependent; may be absent, one-step, or multistep	Explicit finite or receding horizon
State-transition logic	Binary clear/dark rule based on load sign	Preset thresholds or rules	Prediction-informed rule, selection, or	The first action of an optimized control

			optimization	sequence is applied and the optimization is repeated at the next control step
EMS calling point	AfterPredictorBeforeHVACManagers	Implementation dependent	Implementation dependent	Implementation and platform dependent; external co-simulation may also be used

The table summarizes typical characteristics rather than universal definitions, because individual implementations may differ. The present Load strategy is a transparent, low-complexity benchmark for isolating switching-signal effects across a large climate matrix. Its EnergyPlus-predicted load represents the current-timestep load required to meet the applicable thermostat setpoint and does not constitute a future load forecast. The strategy is therefore not a predictive control or MPC framework. The comparison is intended to clarify methodological scope rather than rank controller quality.