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Bringing Solid-State Magnetocaloric Cooling to the Market: A Commercialization Plan

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Energy & Transportation Science Division
Building Technologies Program

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ABSTRACT

Air conditioning has become a staple in American life, bringing improved health, productivity, and comfort to 93% of single-family homes as of 2015, compared to only 76% in 1990. This rise in demand has contributed to the 2.51 quads (12.5%) of total annual energy consumption in residential buildings attributable to space cooling (U.S. Energy Information Administration 2017). Accompanying this upward trend in space cooling has been increased refrigerant use, which has historically contributed to ozone depletion, global warming, or both. The Oak Ridge National Laboratory – along with German-based partner Vacuumschmelze GmbH & Co. KG – is working to reduce energy consumption and refrigerant use through the development of a next-generation, solid-state magnetocaloric cooling system. The purpose of this study is to investigate market potential of these systems in the United States, including information on the industry landscape, market share and unit shipment projections, optimal price points, and barriers to market entry.

1. INTRODUCTION

1.1 MAGNITUDE OF U.S. SPACE COOLING

Air conditioning (AC) has become a staple in American life, bringing improved health, productivity, and comfort to 93% of single-family homes as of 2015, compared to only 76% in 1990 (U.S. Census Bureau 2016). In 2016, space cooling accounted for 2.51 quads (12.5%) of total annual energy consumption in residential buildings. This value is not expected to change significantly over coming decades, forecasted at 2.35 quads (12%) in 2050 (U.S. Energy Information Administration 2017). Because of its massive market size, even small energy efficiency improvements in the residential cooling sector could have a significant impact on U.S energy consumption, greenhouse gas (GHG) emissions, consumer utility bills, and the strain on the electric grid.

Accompanying this growth in space cooling is increased refrigerant use, which has historically contributed to ozone depletion, global warming, or both. Together, global stakeholders have made great strides in replacing harmful refrigerants with better alternatives, and most recently, more than 100 countries, including the United States, adopt an amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer to set an "early freeze date" related to phasing down the production and consumption of hydrofluorocarbons (HFC), a potent GHG commonly used in air conditioning (AC), refrigeration, and foam insulation (Office of the Press Secretary 2016).

Because of its massive (and growing) market size, even small energy efficiency improvements in the residential cooling sector could have a significant impact on U.S energy consumption, GHG emissions, consumer utility bills, and the strain on the electric grid.

1.2 PURSUIT OF SUPERIOR TECHNOLOGY

The U.S. Department of Energy's (DOE) Building Technologies Office diligently works with researchers from industry, national laboratories, and academia in its pursuit of ways to dramatically reduce energy consumption and GHG emissions from heating, ventilating, and air conditioning (HVAC) systems in new and existing buildings. This includes the rollout of more stringent standards and regulatory actions that push manufacturers to find innovative ways to increase efficiency of AC units while still providing a comfortable, well-ventilated space. In addition, nationwide competitions and crowdsourcing campaigns, like DOE's JUMP (Join the Discussion, Unveil Innovation, Motivate Transformation, and Promote Technology-to-Market) are helping to spur innovation and encourage building owners and operators to replace or retrofit older, inefficient units.

Among the next-generation AC technologies research areas under development today are non-traditional cycle (NTC) systems, which can provide sensible and/or latent cooling for buildings without the use of refrigerants, therefore, eliminating direct CO_2 emissions. Furthermore, they can often provide energy savings at high-volume cost similar to today's state-of-the-art. Examples of NTC technologies include those based on absorption/adsorption, magnetocaloric, membrane, electrochemical, elastocaloric, and electrocaloric principles (Goetzler, et al. 2016).

As an example of its commitment to advancing research and development (R&D) of next-generation HVAC technologies, DOE recently awarded Oak Ridge National Laboratory (ORNL) – along with German-based partner Vacuumschmelze GmbH & Co. KG. (VAC) – funding to develop a proof-of-concept prototype of the first fully solid-state magnetocaloric (SMC) AC unit.

1.3 PREPARING FOR MARKET INTRODUCTION

This report lays out a commercialization plan for SMC ACs that addresses key aspects of market readiness. Specifically, it will:

- Explain the competitive advantages of the product relative to comparable technologies;
- Identify the target market segment, size, and application of the product;
- Identify key industry players that could become potential partners and competitors;
- Use energy savings and payback period calculations to estimate maximum annual market share and unit shipments;
- Suggest optimal price premiums based on a desired payback period range;
- Describe the associated value chain and how it differs from that of traditional HVAC equipment;
- Identify and assess potential market and technological barriers; and
- Lay out anticipated steps of a strategic deployment.

2. A TRANSFORMATIVE SOLUTION

2.1 UNDERLYING TECHNOLOGY

2.1.1 Conventional Technology

Vapor compression (VC) technology currently dominates the HVAC market due to its scalability, reliability, compact design, and long history of development/optimization by HVAC industry and other researchers (Goetzer, et al. 2014). A compressor, condenser, evaporator, and throttling device or expansion valve are the key components in these systems, as shown in Figure 1, and a working fluid, or refrigerant, continuously passes through these components, absorbing and releasing heat in the process.

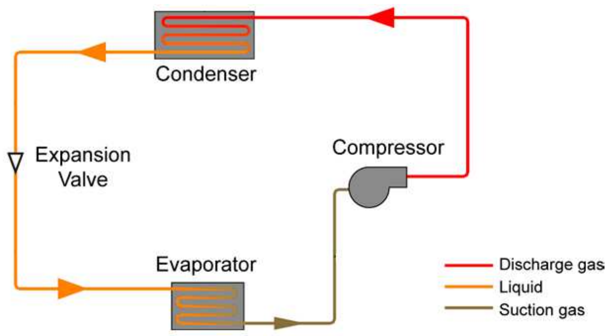

Figure 1: Vapor compression refrigeration cycle (Reis, Nelson, Armer, Johnson, Hirsch, & Doebber, 2015)

Specifically, low pressure liquid refrigerant is passed through the evaporator to absorb heat from the inside of the building. As the refrigerant absorbs heat, it evaporates to form a low-pressure vapor. After the liquid refrigerant completely evaporates, it is sent to the compressor. Compressing the vapor increases the pressure and temperature of the gas. Leaving the compressor as a high-pressure vapor, the refrigerant is sent to the condenser. As the refrigerant passes through it, the vapor, which is at a higher temperature than the ambient air, dissipates heat to its surroundings. This heat loss results in refrigerant condensation back into liquid form. The high-pressure liquid refrigerant then passes through a throttling device before it is returned to the evaporator. By restricting the flow of the refrigerant, the throttling device lowers the pressure of the liquid and, therefore, lowers its boiling point before it returns to the evaporator. In heat pump systems, the flow of the refrigerant can be reversed, causing heat to instead be released into a building.

AC units provide both sensible cooling by lowering the indoor air temperature and latent cooling by removing moisture from the air. In a conventional system, when indoor air moves across the evaporator, some of the moisture in the air condenses onto the evaporator coils, and a pan under the evaporator collects the moisture and drains it away (Holladay 2010).

2.1.2 Novelty of SMC Technology

Unlike the VC cycle, the SMC AC system creates a "magnetocaloric effect" to absorb and remove heat from specialized metals or alloys, eliminating the need for gaseous or liquid refrigerants.

Unlike the traditional VC cycle, the novel SMC AC system exploits the "magnetocaloric effect" to exchange heat from specialized metals, eliminating the need for gaseous or liquid refrigerants. The magnetocaloric effect occurs when a strong magnetic field is applied to a specialized magnetic material, causing it to heat up. This effect occurs in all magnetic materials; however, some (e.g., certain rare earth metals) exhibit it to a greater extent than others (The Ames Laboratory n.d.). The magnetocaloric material is packed in a regenerator bed, and high-conductivity rods composed of copper, brass, or aluminum move in and out of the magnetocaloric material (MCM), exchanging heat with the magnetocaloric material during magnetization and demagnetization effectively pumping heat from one location to another (ACHR News 2015) (Abdelaziz 2016). The full system architecture and cycle are shown in Figures 2 and 3, respectively.

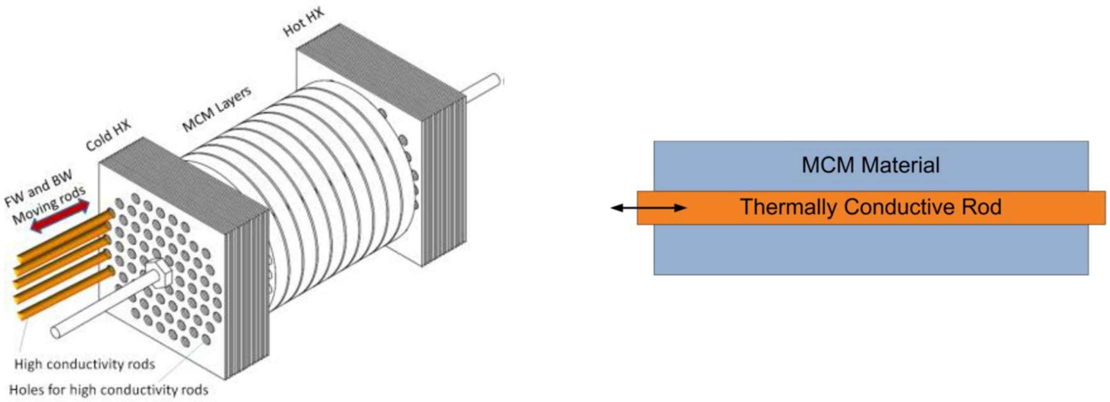

Figure 2: Basic system architecture of SMC technology *(U.S. Department of Energy n.d.)*

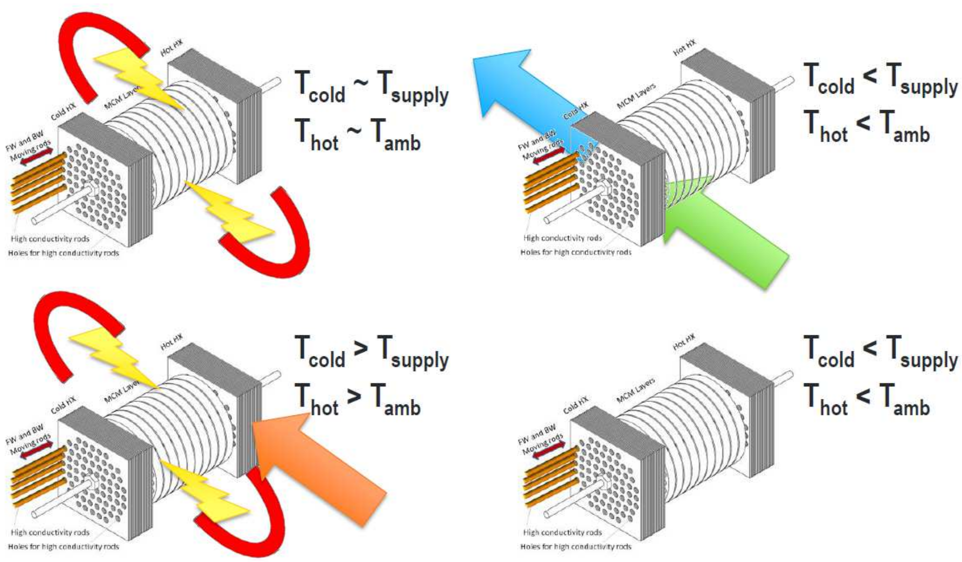

Figure 3: System cycle shows the cooling effect of SMC technology *(ACHR News 2015)*

2.2 COMPETITIVE ADVANTAGES

The SMC AC combines a number of features that, together, make it a transformative technology for the cooling industry by not only addressing the needs of the end-user but also contributing to national energy and GHG emissions reduction goals. These key attributes include the following:

- Improved System Efficiency: Due to its unique system design, this SMC AC unit can improve energy efficiency up to 25% compared to minimum efficiency VC systems (Abdelaziz 2016) (U.S. Department of Energy n.d.). This efficiency gain qualifies the SMC AC for the ENERGY STAR label, which requires a 10% efficiency improvement over the federal standard of (ENERGY STAR n.d.).
- No Refrigerant Required: As a solid-state system, this unit creates a cooling effect by applying a magnetic field to a rare earth metal and using metal rods to transfer the heat out of the building. No liquid or gaseous refrigerants are needed to run the system, so direct refrigerant emissions are impossible. With refrigerants being a mainstay of current AC technologies and a significant

contributor to GHG emissions, a refrigerant-free system has the potential to transform the industry.

- Operating Cost Savings: The high efficiency achieved with this technology will result in reduced consumption of electricity and, therefore, reduced annual utility bills.
- Simpler Composition: This unit eliminates the use of system components such as rotating valves and heat pumps found in conventional magnetocaloric systems, replacing them with simple rod or sheet architecture. As a result, related losses are reduced (Abdelaziz 2016).
- Peak Demand Reduction: Space cooling accounts for a large portion of peak demand in many areas of the country. If applied widely, the SMC unit could reduce the peak demand for utilities during warmer months in due to its lower energy consumption and keep them from having to utilize their least efficient, most polluting electricity generators.

3. INDUSTRY LANDSCAPE

3.1 TARGET MARKET

The first step to understanding the market potential of a novel technology is to define the target market. Since the proof-of-concept prototyping for SMC ACs is starting at a relatively low capacity, the target market is currently limited to 20,000 Btu/h (1.67 ton). Conveniently, this initial capacity range matches quite well with the market for window and through-the-wall room ACs (including heat pumps), which are present in 23% of the 113.6 million single and multi-family residences across the nation (U.S. Energy Information Administration 2009).

Room ACs offer a very affordable and simple-to-install cooling option, but are generally not as efficient as central ducted systems. Table 1 shows the variation in the use of room ACs across the United States. According to the data, residents in the Northeast tend to address their periodic need for AC with less expensive window/wall units instead of costlier central units, making it the most promising region for room AC sales. Since most homes in the South are equipped with central AC equipment, the demand for room ACs is much lower in this region. Table 2 shows that the higher percentages of room ACs are found in apartments and mobile homes, which are less likely to have central ducted AC units (U.S. Energy Information Administration 2009). Therefore, apartment building owners/dwellers in the northeast region appear to be the consumer group most likely to be interested in new room AC products, whereas single-family units in the remainder of the country currently tend to opt for central AC equipment.

Table 1: Distribution of room ACs in the United States, by census region

	CENSUS REGION			
Of homes that use AC, percent that use…	**Northeast**	**Midwest**	**South**	**West**
Central AC Equipment	44%	76%	85%	74%
Room AC units	58%	26%	16%	27%

* More than one may apply.

Table 2: Distribution of room ACs, by housing unit type

	HOUSING UNIT TYPE				
Of homes that use AC, percent that use…	**Single-Family Units**		**Apartments in Buildings with…**		
	Detached	**Attached**	**2-4 Units**	**5 or More Units**	**Mobile Homes**
Central AC Equipment	69%	60%	32%	51%	54%
Room (window/wall) AC units	18%	24%	38%	28%	32%

* More than one may apply.

Although the SMC AC presents a completely new science to space cooling, it is a viable option for both new build and replacement purchases assuming a) installation and maintenance requirements are comparable to conventional units and b) dimensions and weight are comparable to preexisting units, in the case of replacements that need to fit in designated space. For room ACs, this may mean that the unit can easily be situated/secured within a standard size, double-hung window opening; does not exceed the load limitations for the window sill; can plug into a nearby electrical outlet; and accommodate simple operation for the owner. The same requirements would largely apply to higher capacity units; however, the dimension/weight limitations may instead apply to an outside concreate slab or rooftop space.

Because room ACs typically cost several hundreds of dollars, consumers are expected to wait until the end-of-life (approximately 10 years) before seeking out an upgrade unless the cost savings or cooling function benefits are substantially greater than their current unit. The same can be expected of central AC and commercial unit owners since the initial investment is even larger; however, anticipated lifespans of larger units are longer, so the opportunity for long term savings is greater.

It should be noted that while, in its current state, the SMC AC is technically suited for the room AC market segment and there is value to demonstrating it in low-capacity units, certain market dynamics indicate that other AC market segments, where units have higher capacities and longer lifetimes, should be strongly considered as the long-term target market. For instance, room AC shoppers are largely driven by first cost. If they do take lifecycle cost into account, the acceptable payback period is lower for room ACs than larger, longer-lifespan units. Therefore, it is more challenging for a manufacturer to introduce a costly technology into a market segment where margins are already slim. Furthermore, GHG emission reductions and energy savings will be greater if this technology is incorporated into higher-capacity market segments. Finally, maintenance is more standardized/regular at the institution level, usually performed by professional, so consumers would not be faced with new techniques. Until R&D proves that this technology can be successfully scaled up, however, the target market segment for the purposes of this study is room ACs.

3.2 MARKET SIZE

In 2014, the U.S. AC market demand was valued at more than $26.4 billion, and it is anticipated to grow at a compound annual growth rate (CAGR) of more than 8.8% from 2014 to 2020 (Hexa Research, Inc. 2015). According to the Freedonia Group, room ACs accounted for approximately $1.345 billion, or 5%, of this total 2014 market value. This demand is expected to rise to $1.815 billion by 2019 and to $2.225 billion by 2024 (The Freedonia Group 2016).

In its current state, the SMC technology is most technically suited for the room AC market segment. In the long term, however, larger capacity segments (e.g., commercial units) may offer greater market opportunities.

In Figure 4, unit shipments of room ACs are compared to shipments of other common cooling technologies—central ACs and air-source heat pumps (ASHP)—since 2010 (limited by data availability). According to AHAM, room AC shipments reached 6.87 million in 2016, an 8.5% year-on-year increase over 2015. Central ACs and ASHPs also grew in 2016 to 4.90 million and 2.43 million shipments, indicating growth of 8% and 7%, respectively, over 2015 numbers.

Central ACs and ASHPs have directly competed for several decades as they provide cooling to the entire house. Room ACs, on the other hand, indirectly compete with these technologies since they offer an alternative cooling option to homeowners that choose not to invest in a central system. As the figure indicates, the market has consistently been larger for room ACs in recent years, though the total market value is considerably lower. As more homes are built with central AC, room ACs are at risk of losing a small percentage of market share but mostly in regions where cooling is warranted year-round.

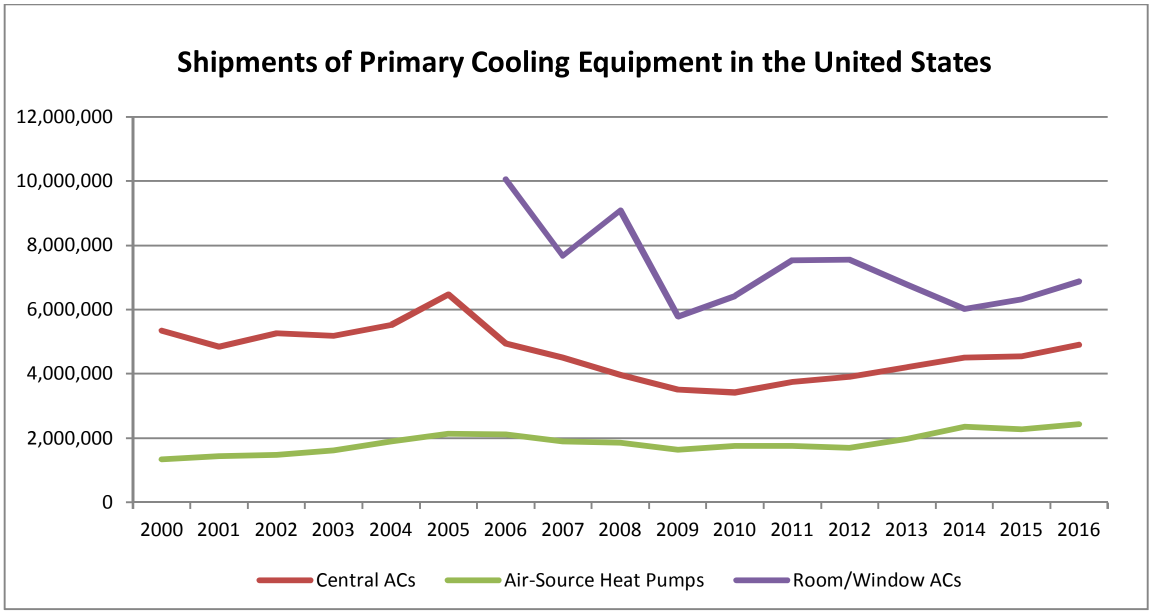

Figure 4: Room ACs have traditionally outsold central ACs and ASHPs
(AHAM 2006-2016) (AHRI 2016)

The initial target market of room ACs (with capacities up to 20,000 Btu/h) is estimated to have annual shipments of 6.7 million units.

The cooling duty of room ACs typically ranges in capacity from 6,000 to 24,000 Btu/h (0.5-2 tons). As stated above, units with capacities up to 20,000 Btu/h (1.67 ton) are of particular interest in this study since it aligns well with the current state of the technology. According to market share data aggregated by AHAM, an estimated 97% of room AC sales falls within this study's target market (up to 20,000 Btu/h) (U.S. Department of Energy 2011). Therefore, the annual shipments for the target market can be estimated by multiplying the 2016 room AC shipment data (6.9 million units) in Figure 4 by 97%. As a result, annual shipments for this study's target market are estimated to be 6.7 million units.

3.3 KEY INDUSTRY PLAYERS

As of 2014, the U.S. HVAC market has been rather consolidated, as shown in Figure 5. Slightly more than half of the market was secured by four manufacturers—Daikin Industries, United Technologies (including subsidiary Carrier), Ingersoll-Rand (including subsidiary Trane), and Lennox—and the remainder of the market was comprised of companies garnering single-digit percentages. It should be noted that the market breakdown in this figure is based on industry value, and the non-residential market represents the larger share of HVAC equipment demand in terms of value since systems used in commercial buildings tend to be larger and more expensive (Freedonia Group 2015). Therefore, this figure is most applicable to

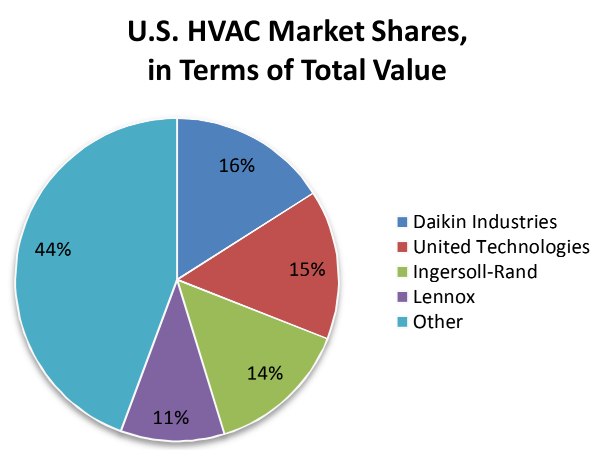

Figure 5: Key players among the broader HVAC market

larger residential and commercial units, which may be applicable the long-term target market for SMC technology.

In the shorter timeframe, a more granular look into the HVAC market—drilling down specifically to room ACs—is needed since the leaders of this submarket may be overshadowed in value-based market breakdowns. Unlike the geographically diverse commercial sector, production of room ACs is dominated by Original Equipment Manufacturers in China and ASEAN[1] countries, including Electrolux, General Electric (GE), Whirlpool, LG, Samsung, Haier, Midea, Gree, Frigidaire, Friedrich, and Sharp (JARN 2017).

Consumers most often purchase their home comfort products (e.g., portable fans, air conditioners, vaporizers/humidifiers, portable room heaters, dehumidifiers, and electric air cleaners) directly through retailers, ranging from electronics retailers to big box and online merchants. Figure 6 breaks down market shares of top retailers in 2014 based on a survey conducted by Home Channel News of more than 150,000 consumers tracking their product purchases of consumer durable products each quarter (TraQline 2014).

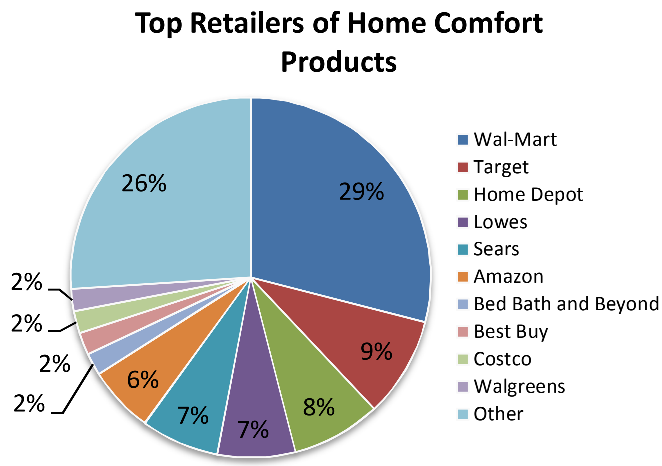

Figure 6: Breakdown of home comfort product retailers

[1] Association of Southeast Asian Nations

4. MARKET POTENTIAL

The market potential of SMC ACs can be assessed by forecasting the maximum penetration into the residential cooling market following commercial viability, as a function of payback period. As determined in Chapter 3 for the purposes of this report, the target market for this technology is limited to residential AC units (including heat pumps) with a cooling capacity of up to 20,000 Btu/h, but this range has the potential to expand long term, depending on test results.

4.1 PAYBACK PERIOD

Payback period is the ratio of the increase in total installed cost (compared to a conventional model) to the decrease in annual average operating cost. The output, expressed in years, tells consumers how long it would take them to recover the additional money they invest, for example, in a SMC AC unit over a comparable vapor-compression-based unit. Calculating the payback period for these AC units, as outlined in the following equation,[2] is the first step in understanding market potential since maximum unit shipment projections are dependent on this value.

$$\text{Simple Payback Period} = \frac{\Delta \text{TIC}}{\Delta \text{OC}} = \frac{\Delta(\text{RC} + \text{IC})}{\text{EC} * \text{ES} * \text{EP}}$$

Where:

TIC = total installed cost of room AC unit ($)
OC = annual operating cost of room AC unit, in this case electricity consumption ($)
RC = retail cost of room AC unit ($)
IC = installation cost of room AC unit ($)
EC = annual electricity consumption of conventional room AC unit (kWh)
ES = estimated energy savings as a result of the SMC AC (%)
EP = national average residential electricity price in 2016 ($/kWh)

Payback periods exceeding the life of a product mean that the increase in total installed cost will likely never be recovered through reduced operating cost. According to DOE's Technical Support Document, the average life of room ACs is 10.5 years (U.S. Department of Energy 2011).

4.1.1 Total Installed Cost

To determine the difference in total installed cost between SMC and comparable vapor-compression-based room AC units, retail price and installation cost data were first gathered on existing inventory. Home Depot's room AC inventory consisting of more than 125 models (including both window and through-the-wall) provided a sufficient sampling to calculate average retail prices for all relevant room AC product classes, and DOE's most recent Technical Support Document for room ACs was used as guidance on typical installation costs for the same product classes. See Table 3 for further details.

[2] No discount rate to discount future operating costs is used in this calculation.

Table 3: Conventional room AC retail price and installation cost averages across relevant product classes

ROOM AC TOTAL INSTALLED COST DATA			
Product Class (PC)	**Market Share***	**Retail Price Average****	**Installation Cost*****
Window (with louvered sides)			
1	31.81%	$147	$82
2	18.65%	$188	$100
3	34.61%	$302	$118
4	4.97%	$492	$136
11	0.83%	$691	$118
Through-the-wall (without louvered sides)			
6	0.10%	x	$115
7	0.41%	$699	$115
8	8.29%	$611	$115
9	0.31%	$550	$115
12	0.10%	$793	$115
14	0%	x	$115

* Source: DOE Technical Support Document for Residential Room AC (2011-4); adjusted to account for PCs not applicable to the target market.
** Based on Home Depot inventory search; "x" indicates that no models were offered, which is in line with the market share.
*** All installation costs for through-the-wall PCs assumed to be the same as PC8, which was set in DOE LCC analysis; PCs 2 and 4 were interpolated/extrapolated based on DOE LCC analysis assumptions for PC1 and 3; PC 11 was assumed to equal PC 3.

Next, weighted averages were calculated for both retail prices and installation costs of each relevant product class based on their market share, also listed in Table 3 The two weighted averages (retail price and installation cost) were then summed to achieve a weighted average for total installed cost, in this case of $376 (see Table 4).

Table 4: TIC weighted average of conventional room ACs

TOTAL INSTALLED COST CALCULATIONS	
Weighted average unit retail price	$272
Weighted average unit installation cost	$104
Weighted average total installed cost	**$376**

For the purposes of this study, three hypothetical price premiums for the total installed cost of SMC ACs relative to the above conventional model were investigated: **$50, $100, and $200**. These translate to total installed costs of $426, $476, and $576.

4.1.2 Operating Cost

The operating cost of a room AC is the product of electricity consumption (i.e., “unit size” x “operating time” / “unit EER”) and residential electricity price. Similar to the total installed cost calculations above, key data points for relevant product classes (e.g., average EER and unit size for comparable vapor-compression AC units) were derived using Home Depot’s room AC available inventory (see Table 5).

Table 5: Conventional room AC EER and size averages across relevant product classes

ROOM AC UNIT EFFICIENCY DATA			
Product Class (PC)*	Market Share**	Average EER***	Average Unit Size (Btu/h)***
Window (with louvered sides)			
1	31.81%	11.2	5,031
2	18.65%	11.4	6,025
3	34.61%	11.6	9,979
4	4.97%	11.7	16,450
11	0.83%	9.9	12,633
Through-the-wall (without louvered sides)			
6	0.10%	x	x
7	0.41%	11.1	6,600
8	8.29%	10.3	10,535
9	0.31%	9.3	14,000
12	0.10%	9.9	9,350
14	0%	x	x

* As defined in EERE-2007-BT-STD-0010: Chapter 3
** Adjusted to account for PCs not applicable to the target market.
*** Based on Home Depot inventory search; "x" indicates that no models were offered, which is in line with the market share.

Next, weighted averages were calculated for both EERs and unit sizes of each relevant product class based on their market share, also listed in Table 5. The weighted average unit size was then multiplied by the average room AC operating time and then divided by the weighted average EER to achieve the weighted average for electricity consumption, resulting in 534 kWh/yr. Finally, the weighted average electricity consumption was multiplied by the 2016 residential electricity price national average of $0.1255/kWh (U.S. Energy Information Administration 2016) to reach the weighted average annual operating cost of conventional room ACs, as shown in Table 6.

Table 6: Electricity consumption weighted average of conventional room ACs

ELECTRICITY CONSUMPTION WEIGHTED AVERAGE CALCULATIONS	
Weighted average unit EER	11.3
Weighted average unit size (Btu/h)	8,055
Average operating time (h/yr)	750
Weighted average electricity consumption (kWh/y)	534
Weighted average annual operating cost	**$67**

For the purposes of this study, three hypothetical operating cost savings achievable with a SMC relative to the above conventional model were investigated: **5%, 15%, and 25%**. These translate to annual operating cost savings of $3.35, $10.05, and $16.75.

4.1.3 Resulting Payback Periods

Using the inputs above, payback periods were calculated for SMC room ACs, relative to average conventional room ACs operating under similar conditions, resulting in as low as three years. Of the nine scenarios investigated (see Table 7), four resulted in payback periods less than the average room AC lifespan of 10.5 years (denoted by yellow and green cells), and two resulted in payback periods that fall within an acceptable range (2.5 to 5 years) for most residential HVAC appliances (denoted by green cells). Red cells denote payback periods that exceed the average room AC lifespan and are, therefore, considered inviable to success market introduction. However, it is worth noting that homeowner payback period expectations are likely lower for room ACs compared to most residential HVAC appliances since their average life expectancy is lower.

Table 7: Summary of hypothetical scenarios for SMC AC payback periods

SIMPLE PAYBACK PERIOD		Total Installed Cost Premium		
		$50	**$100**	**$200**
Operating Cost Savings	**5%**	15	30	60
	15%	5	10	20
	25%	3	6	12

Since the project team is still in the research and testing phase, the payback period assumptions above are subject to change, and minor modifications can have significant impacts on project unit shipments and optimal price point, discussed in upcoming sections.

4.2 MAXIMUM MARKET PENETRATION PROJECTIONS

The DOE Building Technologies Office provides guidance for estimating market penetration for a new technology based on an understanding of the technical, economic, and market dynamics. One method suggested in their "Guide for Evaluation of Energy Savings Potential" (Building Technologies Program 2005) for estimating market penetration is based on payback analysis, which is illustrated in Figure 7 for HVAC equipment.

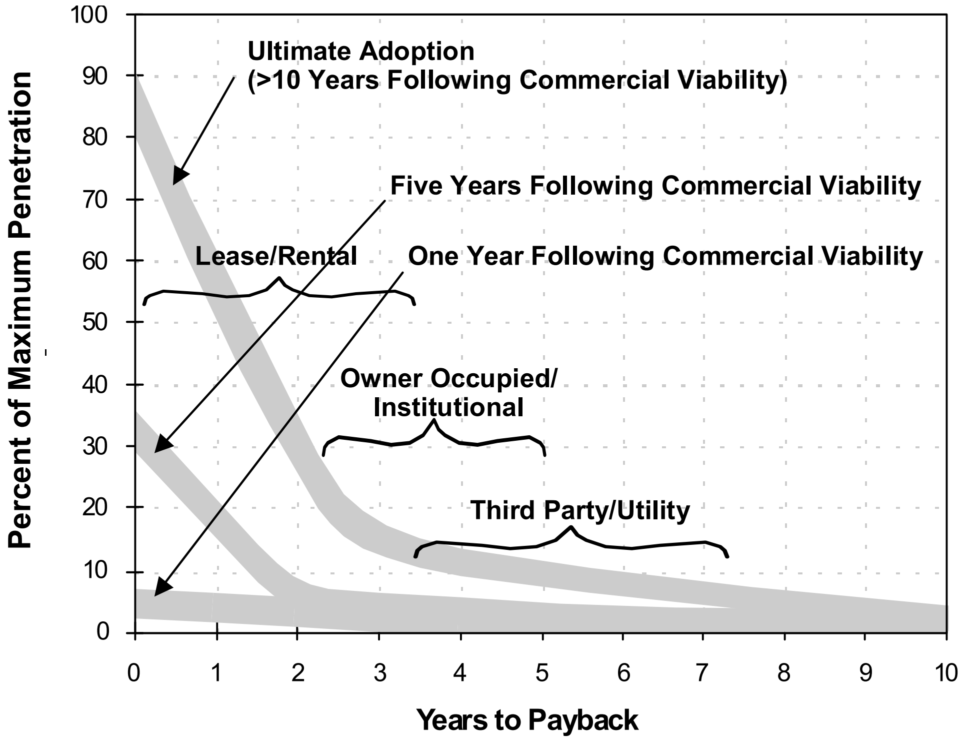

Figure 7: Relationship between payback period and market penetration for HVAC equipment at certain periods of commercial viability (Source: DOE Building Technologies Program)

Using the payback periods in Table 7 that fall within the "acceptable" range (i.e., 3 and 5 years, shaded green), the correlating maximum penetration rates of this technology into the room AC market were estimated. Table 8 provides percent ranges to account for the fuzziness associated with this approach, hence, the wide grey bands in Figure 7 that represent each commercial viability scenario.

Table 8: Level of maximum penetration (%) at different points in time following commercial viability

% OF MAX PENETRATION OF SMC AC UNITS INTO RESIDENTIAL ROOM AC MARKET			
	One Year Following Commercial Viability	Five Years Following Commercial Viability	Ultimate Adoption (>10 Years Following Commercial Viability)
3-Year Payback	0-5%	2-7%	13-18%
5-Year Payback	0-3%	1-5%	8-12%

Assuming the room AC market maintains steady shipments for the foreseeable future (at 2016's forecasted 6.7 million units), Table 8's maximum penetration percentages can be translated into estimated maximum unit shipments in the room AC market at one, five, and over ten years following commercial viability. These calculations are summarized in Table 9.

Table 9: Level of maximum penetration (unit shipments) at different points in time following commercial viability, based on 2016 forecasted unit shipments

MAXIMUM ANNUAL SMC AC UNIT SHIPMENTS INTO ROOM AC MARKET			
	One Year Following Commercial Viability	Five Years Following Commercial Viability	Ultimate Adoption (>10 Years Following Commercial Viability)

3-Year Payback	0 – 335,000	134,000 – 469,000	871,000 – 1,206,000
5-Year Payback	0 – 201,000	67,000 – 335,000	536,000 – 804,000

4.3 OPTIMAL PRICE PREMIUM

Manufacturers commonly reference payback period information when setting price premiums for appliances since consumers may weigh estimated operating cost savings against the additional upfront cost. As mentioned above, a payback period between 2.5 and 5 years is sought by most prospective residential HVAC appliance customers (e.g., home/building owners, institutions). For appliances with a shorter-than-average life expectancy, however, like room ACs, the preferred payback period is often lower, perhaps 1.5-3 years. Therefore, the ORNL team suggests pricing the SMC AC at an amount that would deliver such payback periods. Table 10 provides a breakdown of price premiums that correlate with these payback period ranges. Calculations assume the same weighted average retail price, installation cost, and operating cost for conventional room ACs as used in section 4.1.1**: $272, $104, and $67,** respectively.

Table 10: Pricing guidance for SMC ACs based on desired payback period

TARGET PBP (YR)	ANNUAL OPERATING COST SAVINGS		ALLOWABLE PRICE PREMIUM	RETAIL PRICE SHOULD NOT EXCEED *
1	5%	$3.35	$3.35	$275.71
	15%	$10.05	$10.05	$282.41
	25%	$16.75	$16.75	$289.11
2	5%	$3.35	$6.70	$279.06
	15%	$10.05	$20.10	$292.46
	25%	$16.75	$33.50	$305.86
3	5%	$3.35	$10.05	$282.41
	15%	$10.05	$30.15	$302.51
	25%	$16.75	$50.25	$322.61
4	5%	$3.35	$13.40	$285.76
	15%	$10.05	$40.20	$312.56
	25%	$16.75	$67.00	$339.36
5	5%	$3.35	$16.75	$289.11
	15%	$10.05	$50.25	$322.61
	25%	$16.75	$83.75	$356.11

* Weighted Average Room AC Retail Price = $272

5. STEPS TOWARD SUCCESSFUL MARKET ENTRY

5.1 UNDERSTANDING THE VALUE CHAIN

As the product progresses through a value chain, it gains worth with each key activity, ultimately delivering maximum value to the end user. In the case of conventional room ACs, the value chain spans from raw material acquisition for ACs to post-installation maintenance (see Figure 8). When evaluating new technologies, value chain analysis is imperative since it allows you to see how cost competitive you are within the marketplace (i.e. how the associated costs of the technology in question compare to major competitors). Through this assessment, areas that warrant further thought are identified, which could aid in eliminating various market and technological barriers. Ways to more seamlessly integrate members within the chain may become more apparent as well.

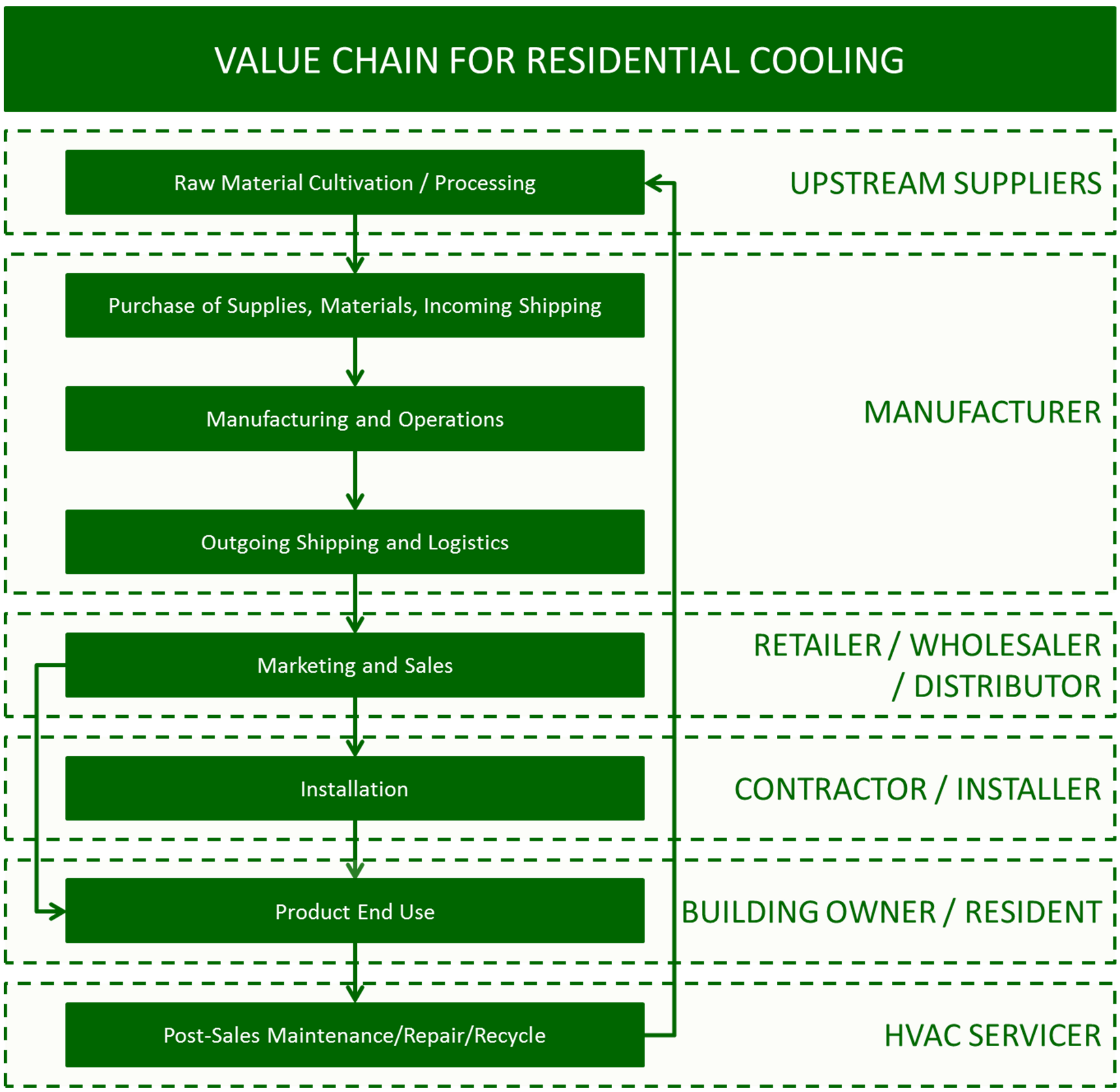

Figure 8: Traditional residential HVAC value chain, linking primary activities to responsible parties

With the value chain defined, differences between conventional product lines (e.g., vapor compression-based ACs) and upcoming ones (e.g., SMC ACs) can be identified, which can be used to estimate relative costs differences at each stage. These differences are detailed in Table 11.

Table 11: Overhead cost differences are anticipated throughout most steps of the value chain

ANTICIPATED OVERHEAD COST DIFFERENCES BETWEEN MAGNETOCALORIC AND VAPOR COMPRESSION RESIDENTIAL COOLING		
	COST/COMPLEXITY INFLUENCERS	ANTICIPATED DIFFERENCE
Raw Material Cultivation / Processing	• Difference in cost to acquire/prepare/assemble/ package raw material or component?	Significant additional cost
Purchase of Supplies, Materials, Incoming Shipping	• Difference in shipping cost, point of origin? • Difference in mode of transportation? • Difference in materials handling/storage methods?	Moderate cost saving
Manufacturing and Operations	• Assuming economies of scale, difference in manufacturing cost per appliance? • Capital costs of new/repurposed production line (e.g., new machine tools, downtime)? • Difference in packaging process?	Moderate additional cost
Outgoing Shipping and Logistics	• Difference in shipping cost, destination? • Difference in mode of transportation? • Difference in materials handling/storage methods?	None
Marketing and Retail Sales	• Difference in media/branding/outreach investments required? • Difference in retail price? • Applicable purchase discounts (e.g., ENERGY STAR tax credits)?	Moderate additional cost
Installation	• Difference in technique? • Difference in required tools, materials? • Difference in required labor?	None
Product End Use	• Difference in operating cost? • Available utility incentives?	Moderate cost saving
After-Sale Maintenance/Repair/Recycle	• Difference in diagnostic techniques? • Difference in required labor? • Difference in replacement parts/fluids, costs? • Difference in time/cost required to properly recycle components (if applicable)?	Moderate additional cost

5.2 ASSESSING THE BARRIERS

Associated with most key activity in Figure 8's value chain are important barriers to market entry that should not be overlooked. These barriers are typically defined as either:

- Technological: Obstacles that likely must be addressed through further research and development efforts, and are typically improved upon in subsequent product generations; or
- Market: Obstacles toward achieving desired unit sales and consumer's interest, even if the product and underlying technology are considered mature.

Regulatory obstacles, often in the form of environmental, health, and safety standards enforced by government entities, must also be sufficiently addressed for a product to even be considered for market deployment. For SMC technology, this may include ensuring that sustained use of rare earth (RE) metals (for both the permanent magnet and MCM) in household appliances does not pose any health or safety threat to consumers. The use of permanent magnets, primarily neodymium, is widespread in electronic applications. Assuming the volumes of permanent magnets and the resulting magnetic fields are comparable, no concerns are anticipated, but further research should be conducted to determine if specific testing is required.[3] Regarding the use of MCM in household appliances, no standards appear to be in place at this time so it is unclear if new testing and/or paperwork is required.[4]

5.2.1 Numerous Stakeholders Involved

As demonstrated above, a successful market introduction for SMC ACs places responsibility on almost all stakeholder groups, each with their own set of challenges. Figure 9 displays some of these anticipated technological and market barriers, broken down by the responsible parties. The party bearing the heaviest burden is the manufacturer, who will spend years developing the product, retooling its plants, and producing sufficient volumes. However, without the commitment from upstream and downstream players, manufacturers are at risk of underwhelming sales and limited end use.

[3] The World Health Organization lists typical magnetic field strengths of household appliances at various distances in its Electromagnetic Fields home page: http://www.who.int/peh-emf/about/WhatisEMF/en/index3.html.

[4] No Federal regulations have been set in the United States to limit exposure levels of magnetic fields, but guidelines have been set by the International Commission on Non-Ionizing Radiation Protection (an affiliate of the World Health Organization) for static magnetic fields, like those sustained by permanent magnets. Specifically, acute exposure to the general public should not exceed 400 mT for any part of the body. Much lower restriction levels have been implemented for special environments (e.g., operation of MRIs) to prevent inadvertent harmful exposure of people with high-risk medical circumstances (International Electrotechnical Commission 2010).

Figure 9: Anticipated technological and market barriers for SMC AC units

5.2.1.1 Upstream Suppliers

Material Supply Concerns. Unlike traditional units, SMC ACs use RE metals—like lanthanum for MCM, and neodymium and dysprosium for permanent magnets—to provide cooling. The global market for RE metals has a history of volatility originating from rising demand in competing markets and political factors (e.g., export quotas by China where more than 90% of the world's RE metal supply resides), resulting in limited global supply/availability. Furthermore, because China has traditionally been able to produce RE metals at roughly one-half the prices of other countries due to lax environmental mining constraints, global competitors have been deterred from entering the market, further limiting availability (Ives 2013). Three major supply mines exist in the United States: Mountain Pass, Bear Lodge and Bokan Mountain, each offering cerium, lanthanum, neodymium, and europium supplies (plus yttrium and dysprosium at the latter) (Wang, et al. 2015); however, production at Mountain Pass ceased in 2015 when the owners filed for bankruptcy, but the mine is still being maintained in anticipation for a new buyer (Yoders 2016).

As demand for RE metals ramped up in recent years, China enforced export quotas in an effort to protect against resource exploitation and improve environmental conditions. Serious supply concerns caused prices to skyrocket in 2011, as shown in Figure 10. Neodymium, along with most RE metals, have since returned to relatively normal levels following China's quota lift in 2014 (Rowlatt 2014).

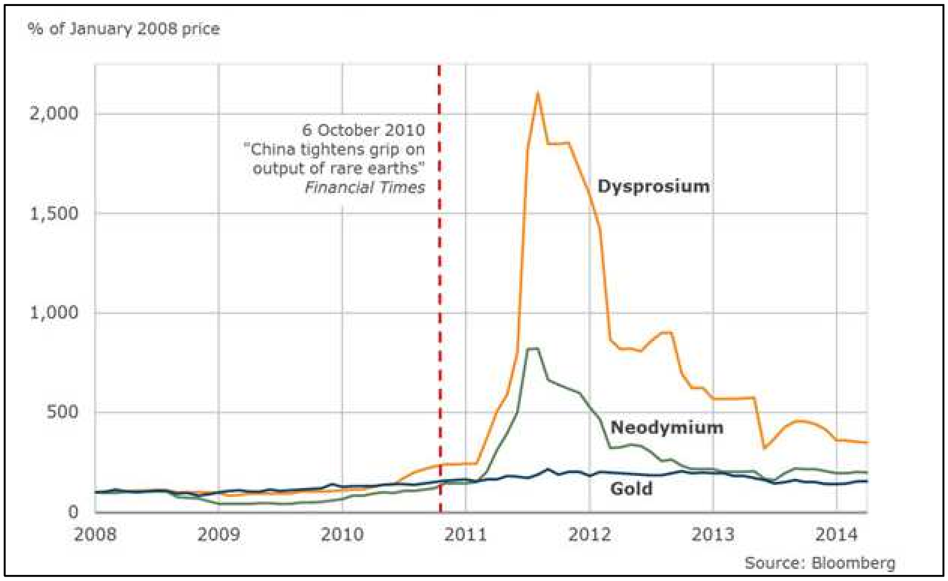

Figure 10: Rare earth metal prices spiked in 2011 amidst Chinese export limitation concerns (Source: Bloomberg)

According to DOE's Critical Materials Strategy, dysprosium and neodymium (used to meet the SMC AC's magnetic needs) are among five RE elements deemed "critical" in the short term (present-2015), as shown in Figure 11, with respect to importance to clean energy and supply risk due to growing green-tech demand (e.g., electric motors in hybrid/electric vehicles and generators in wind turbines). DOE's strategy also projected shortages of neodymium by 2025, but this timeframe might be expedited since this projection was made prior to the close of Mountain Pass. Lanthanum (used to meet the SMC AC's MCM needs) was considered "near-critical" and is not quite as problematic, as it is the second most abundant RE element (U.S. Department of Energy 2011).

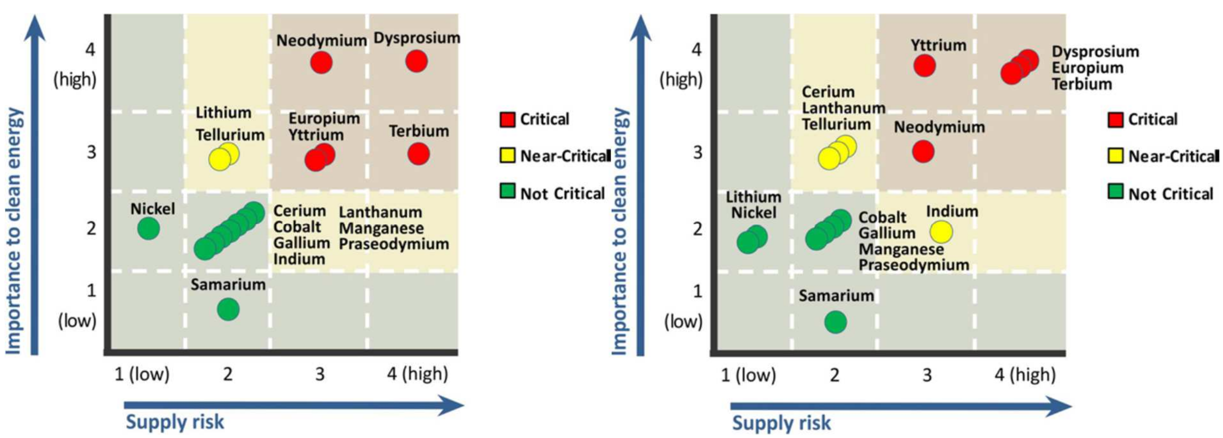

Figure 11: Short-term (present – 2015), left, and medium-term (2015-2025), right, criticality mix, according to DOE's 2011 Critical Materials Strategy *(U.S. Department of Energy 2011)*

These supply concerns have motivated countries to begin producing and refining RE metals in other parts of the world to lessen dependence on China. It has also driven private industry to invest in R&D efforts to reduce RE volumes in various products and to identify less expensive material substitutes.

5.2.1.2 Manufacturer

Plant Retooling (or New Construction). If an established manufacturer choses to adopt the SMC technology and take it to market, either considerable adjustments will need to be made to existing plant production lines (previously designed for conventional vapor compression models) or new lines will need to be constructed. As a result, the manufacturer is faced with major capital costs associated with new machinery and tools, plus loss-making downtime. Therefore, a truly outstanding, revolutionary product (i.e. a better performing, low/no GWP solution that is highly cost competitive with competing technology) would likely be needed for an established manufacturer to take on such an investment.

Cost Premium. At present, most residential AC purchasing decisions are based on first cost, which tends to result in sales of relatively lowest-cost, lowest-efficiency units. Therefore, it is imperative that manufacturers achieve a cost premium that is considered negligible to consumers (while still reaching acceptable profit margins) for room AC models. More leeway in price premiums exists with larger-capacity, longer-lifetime models (e.g., commercial rooftops) when consumers are more thoughtful of lifecycle costs. As the product reaches economies of scale, this challenge should begin to subside. Until then, a targeted marketing and educational campaign will be required to focus consumer attention on the operational cost savings of the technology, which will outweigh the upfront cost premium.

Design Constraints. The SMC AC unit may exhibit unconventional dimensions and weight due to its unique design and components. As the team builds its prototype, it should be cognizant of existing industry limitations that could restrict the design. For example, in a 2011 direct final rule for energy conservation standards (76 FR 22453), DOE set weight and dimension restrictions for room ACs. Included in this rule is a total weight limit of 50 lb. for Product Class 1 baseline units.[5] By establishing this limit (suggested by AHAM), manufacturers avoid exceeding guidelines set by the Occupational Safety and Health Administration and the National Institute for Occupational Safety and Health for single-person lifting and to avoid the possible reduction in consumer utility since these units are often removed seasonally by the building owner (U.S. National Archives and Records Administration 2011). DOE chose not to establish weight limits for other investigated product classes since baseline units of these product classes already exceeded the 50 lb. weight limit.

The same 2011 direct final rule established maximum chassis widths and heights (but not depths) for all room AC product classes with louvered sides. DOE based these dimensions on the largest R-410A room ACs in each product class available for purchase at the time. DOE chose not to establish height and weight restrictions on non-louvered models since most of these products are replacements and, therefore, are already restricted to existing building sleeves, which are usually built into the existing building structure.

Table 12: Maximum width and height for room ACs established in 76 FR 22453

PRODUCT CLASS	MAX WIDTH AND HEIGHT (IN.)*
1 (less than 6,000 Btu/h)	19.75 x 14.0
3 (8,000-13,999 Btu/h)	25.94 x 15.94
5A (20,000-27,999 Btu/h)	26 x 17.5
5B (28,000 Btu/h or more)	28 x 20.19

*Based on R-410A max-tech unit on the market

[5] Product Class 1 includes room ACs with cooling capacities of less than 6,000 Btu/h with louvered sides and without reverse cycle.

Noise Level. The SMC AC unit may be louder than some room ACs, which may lessen overall product appeal. While noise levels range widely, room ACs are typically around 55 dB. Therefore, the SMC AC unit should aim to be comparable. From a standards perspective, no limitations are currently in place for acoustic noise levels of room ACs. In 2014, the ENERGY STAR™ program proposed an indoor sound power level limit of 60 dB(A) in its Product Specifications for room ACs, which matches EU EcoDesign regulations, but this limit was omitted from the final version due to stakeholder feedback. It should also be noted that some states or municipalities regulate environmental noise from stationary sources (e.g., air conditioners).

Reliability. As this technology is still in the development phase, the long-term reliability of the system has not been proven. Consumers may not want to invest in a technology whose durability is questionable, especially when established technology options with proven endurance are available as an alternative.

Product Marketing. Shelf space is extremely valuable for major wholesalers/distributors, and convincing them to make room for a new technology can be quite challenging, given that retailers are inclined to stick with complete product lines from a handful of well-known manufacturers with strong sales records. Therefore, for the SMC unit to make it on the shelves, the manufacturer must provide compelling evidence to the wholesaler/distributor that it will sell. As explained above, the unit will likely be priced higher than conventional vapor compression technologies, so providing marketing materials to wholesalers/distributors that highlights the sizeable energy and operating cost savings achievable over the lifetime of the AC unit will be essential.

Also, if worked into an existing manufacturer's product line, a wholesaler's reluctance to carry it may be lessened. The high efficiency of the unit will also qualify it for the appealing ENERGY STAR™ label, which provides a recognizable symbol and clearly explains to the consumer why purchasing this unit is in their best interest. Wholesalers/distributors will also be tasked with educating their sales teams on the benefits and optimal applications of the technology.

5.2.1.3 Wholesaler / Distributor

While wholesalers/distributors may face barriers associated with introducing SMC ACs into the market (e.g., explaining new concepts to customers and educating their salesforce), they are not expected to bear any burden related to their market success.

5.2.1.4 Contractor / Installer

New Installation Techniques. As with any new technology, a concerted effort must be made to educate contractors and installers on the functionality and correct installation and operation of this AC technology. Contractors and installers are familiar with vapor compression AC technologies, but magnet-based systems are not familiar. If they are not provided with an in-depth explanation of the system, they are likely to recommend a familiar technology, i.e. vapor compression, or possibly install the system incorrectly. Both outcomes would ultimately turn the consumer off of magnetic cooling systems. Left to their own devices, most people will not make the effort to learn about a new technology if easier options exist.

5.2.1.5 Building Owner / Resident

Consumer Acceptance of New Technology. Consumers are generally hesitant to invest in a completely foreign technology. They prefer to go with a known quantity rather than take a chance on something new. To overcome this reluctance, the energy and cost benefits will need to be clearly defined on the product's packaging and marketing materials. Additionally, sales clerks should be well versed on the benefits of the technology and the basic functionality of the system. End-user targeted advertising should focus on the qualities most important to the consumer: lower operating costs, ease of use, and lower environmental impact.

5.2.1.6 HVAC Servicer

New Maintenance Techniques. Similar to the installers and contractors, HVAC servicers will need to be educated on this technology so that they feel comfortable working on it and discussing it with their clients. Oftentimes, technicians are called in when an AC unit fails and are consulted in the customer's selection of a new unit. This makes them a critical component of the marketing chain for this technology. The more confident technicians are in the technology, the more comfortable they will feel recommending this technology to their customers, and more than likely, the more comfortable the consumer will feel purchasing the technology. However, if technicians are not adequately familiar with the technology, they are likely to direct consumers towards a more traditional technology.

Proper Rare Earth Element Recycling. Due to the low availability and growing demand of RE materials, recycling of these elements may prove to be pivotal for securing future supply. It is imperative that SMC AC units enter this process at the end of their usable life. Unfortunately, this process comes with several major challenges. First, recycling of RE elements it is currently not economically feasible since these elements appear in low densities in recycled products and would require expensive chemical processing to recover. In addition, the resulting products would not have a high intrinsic value as they would have to undergo additional materials processing for reuse.

Numerous companies in competing markets (e.g., electronics, electric vehicles, wind turbines) are pursuing cleaner and more cost-effective recycling solutions and may have best practices that can be adopted by the AC industry. For example, Honda and Japan Metals & Chemicals are able to recover 80% of RE from used NiMH batteries with molten salt electrolysis; Infinium, Inc. has developed a carbon free method for processing certain REs, and Fraunhofer is using melt spinning to recover RE from magnets that can be reused with minimal processing (Booten, Mann, et al. 2017).

5.2.2 Prioritizing Barriers

Some barriers are more challenging to overcome than others. Some barriers may have a potentially huge impact on future sales but are relatively easy to address, and vice versa. Others may have a potentially minor impact on future sales and can be addressed with only minimal effort. On the other end of the spectrum where a barrier is simply too costly or technically challenging to overcome, it may even be considered a "show-stopper."

To realistically assess where barriers of SMC units fall on this spectrum, a group of industry experts was polled by the research team. Each expert was asked to assign values (ranging from 1 to 10) to:

- A barrier's potential impact on market success (1= very small and 10 = very large)
- The degree of difficulty associated with overcoming the barrier (1= very simple and 10 = very difficult)

Expert responses were plotted in Figure 12 where the plot area is divided into three major sections conveying how critical it is that the barrier be sufficiently addressed. Based on their expert opinions, it appears that design constraints (more specifically, unit dimensions and weight) currently pose the greatest risk to the SMC AC's successful market debut. Barriers rated as "moderate risk" include the cost premium, material supply concerns, proper rare earth element recycling, product reliability, noise level, and new maintenance techniques. For a full list of experts polled in this study, see Appendix A.

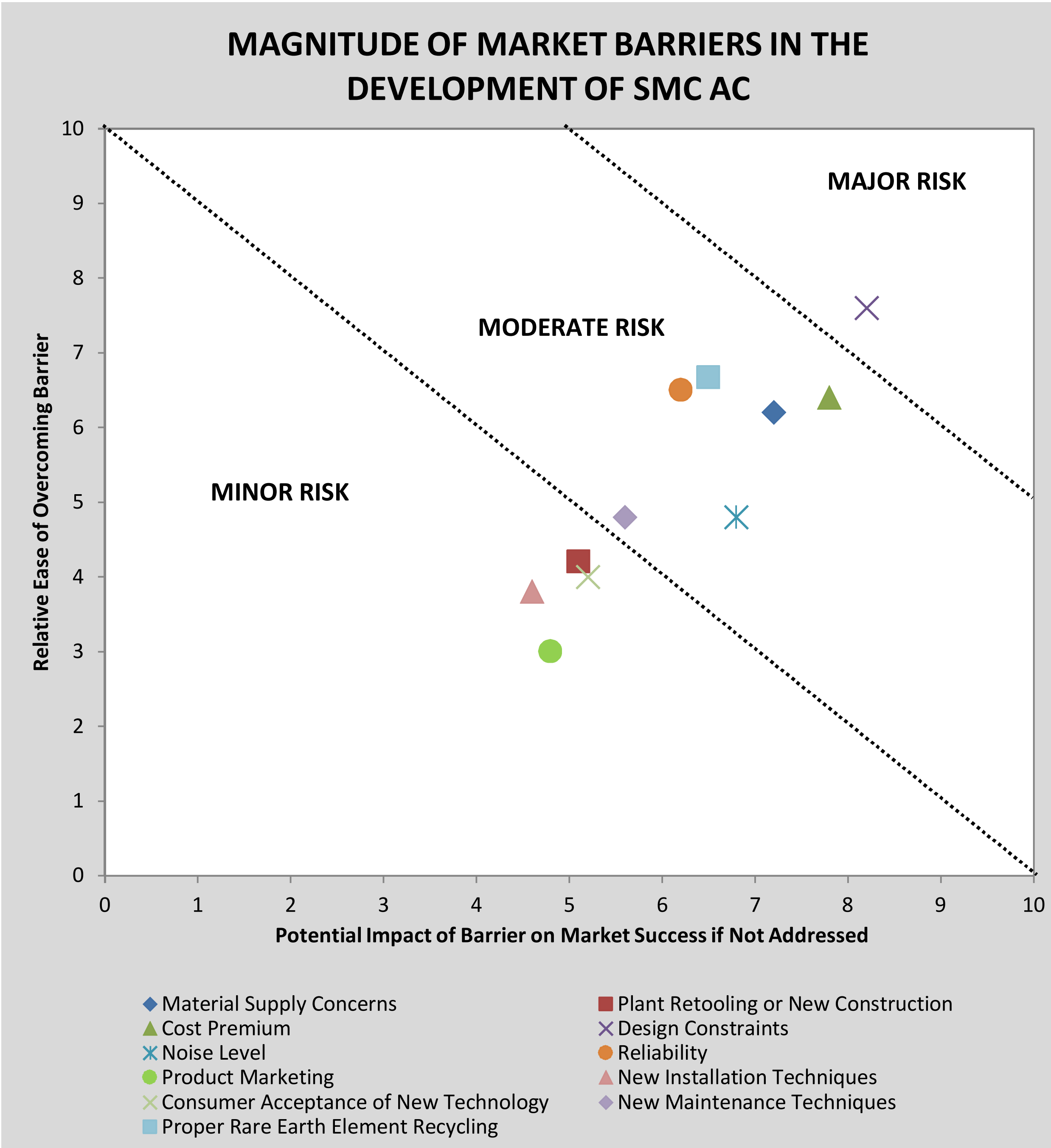

Figure 12: Barriers categorized by amount of additional focus needed

6. STRATEGIC DEPLOYMENT

Successful deployment of a clean energy technology requires thoughtful, methodical planning. As shown in Figure 13, it starts with technology creation where an invention undergoes considerable investigation, is then introduced to the market, and extends through commercialization (U.S. Department of Energy n.d.). Each key phase as it relates to the deployment of SMC AC technology is described below.

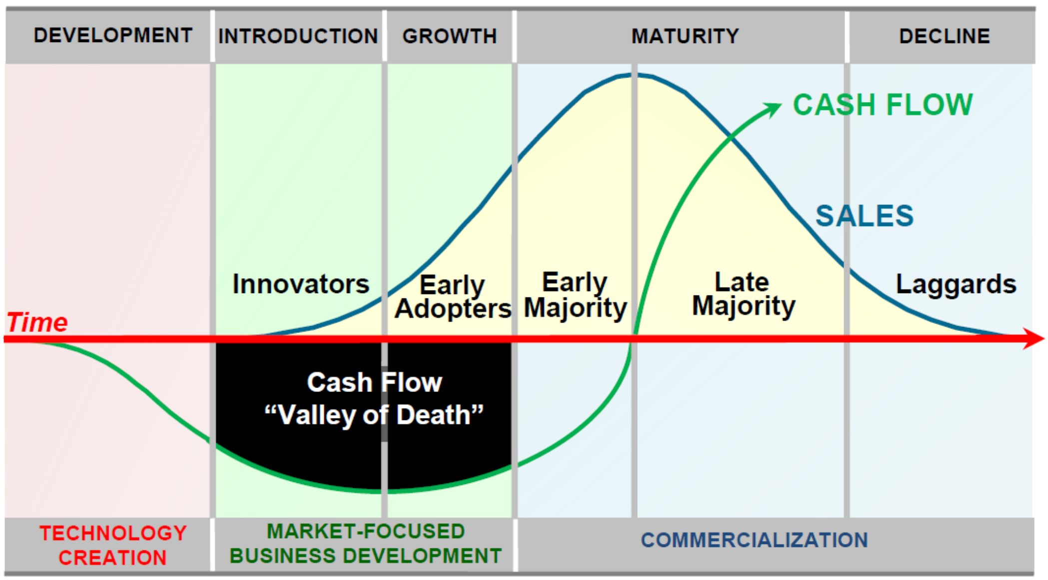

Figure 13: Common technology deployment timeline *(U.S. Department of Energy n.d.)*

6.1.1 Technology Creation

The "Technology Creation" phase, shaded red in Figure 13, often starts with an innovative concept that theoretically surpasses the state of the art. Next, funding permitting, this concept may evolve to bench-scale or prototype testing to actually "prove" the concept through tangible equipment and materials. Once data is collected and analyzed, decisions can be drawn on whether the technology shows signs of competing in the market, based on preliminary market assessments often conducted in parallel. If it shows promising, further research can be conducted to focus on improving various characteristics in preparation for market introduction. In this phase, typical primary investors for high-risk, clean energy technology development often include DOE, national laboratories, and cost-sharing industry partners.

Currently, ORNL's team is operating within this development phase, bringing a proof-of-concept prototype of the first fully SMC AC to fruition. Made possible through a DOE Funding Opportunity Announcement, which included cost-sharing, ORNL teamed with Vacuumschmelze, an MCM supplier, to collaborate on the project from the ground up. Testing is underway to determine if lab results are in line with theoretical calculations, and this paper informs the team (and other stakeholders) of the technology's market potential. As R&D progresses, the ORNL team should identify outreach outlets and platforms in preparation for sharing the competitive advantages of the SMC AC unit with potential industry partners. Such avenues may include industry journal publications, trade show presence, conference presentations, and webinar appearances. Inviting potential industry partners to observe the prototype in operation and hear about upcoming R&D plans may also peak interest and establish key relationships early on.

After prototype completion, the team may choose to make additional improvements to the design and possibly advance to a demonstration project to test it in real-world conditions. Here, the team can identify opportunities to further increase efficiencies and reduce costs (e.g., material reduction), as well as to ensure the product is sufficiently addressing customer needs (e.g., ease of use, noise level, comfort level).

6.1.2 Market-Focused Business Development

Once a clean energy technology is created and has been determined to have the potential of a strong market competitor, focus shifts toward establishing the market by building product awareness and demand. Early adopters may already be eager to purchase the technology once it hits the market, but considerable efforts will be needed to expand the market to the average homeowner, who is naturally reluctant to change.

Accompanying this shift in focus is often the abrupt ending of public sector funding and the beginning of the search for private sector financing. As shown in Figure 13, the entity moving forward is faced with the impending cash flow "Valley of Death" when major investments mount before sales accumulate. For entrepreneurs interested in forming a new business around the technology, investments from seed/angel investors, or possibly equity financing, may be sought to bridge this gap. Helpful suggestions for navigating the "Valley of Death" are detailed in (Murphy and Edwards 2003).

Partnering with a reputable, well-established room AC manufacturer that is interested in adopting a transformative technology amidst stricter standards and regulations might ease market introduction of the SMC technology.

Another common path to commercialization for research teams is to enlist the aid of their own national laboratory's technology transfer department to help match their market-ready technology with appropriate industry players through licensing opportunities. This move often makes most sense when a market is extremely competitive and dominated by a few major players, resulting in a high barrier to entry. If the ORNL team chooses to pursue commercialization by licensing their SMC technology to an appliance manufacturer, key qualities to consider may include:

- A reputable, well-established manufacturer in the cooling industry capable of relatively easily integrating this design change into existing plant lines and supply chain;
- Ability to capitalize on their industry position to endorse/promote new products, lessening the apprehension many consumers may associate with trying a new or early-generation technology, and raise public awareness regarding the technological, energy-saving, and environmental benefits of this product;
- Strong brand recognition, reputation of quality appliances, widespread presence, and appealing design aesthetic; and
- Positive past experiences working with national laboratories during the R&D and/or licensing phases.

If one of the major room AC manufacturers identified in section 3.3 is interested in adopting a transformative technology amidst stricter standards and regulations, they might be a strong match for the SMC AC technology. Another possibility would be contacting refrigeration manufacturers investigating magnetocaloric technology in their product line since they could consolidate investments associated with upstream material acquisition and retooling plants. GE and Haier are examples of major appliance manufacturers currently developing magnetocaloric refrigeration technology.

6.1.3 **Commercialization**

The final deployment phase, referred to as "Commercialization," focuses on maintaining market share once it has been established. This phase also accommodates product differentiation, expanding upon the original design for applications in complementary markets. For SMC ACs, this could mean growing from smaller capacity units (e.g., room ACs) to centralized residential AC units or possibly commercial units. The opportunity also exists during this phase to expand distributor channels, broadening sales potential.

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APPENDIX A. INDUSTRY EXPERTS

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Name	Affiliation	Title
Alex Barcza	VACUUMSCHMELZE	R&D Group Leader and Expert in Magnetocaloric Alloys
David Beers	GE Appliances	Director of Technology
	IIR's Industry Sub-Working Group on Magnetic Refrigeration	Co-Chair
Masud Chowdhury	AHAM	Product Regulatory & Standards Engineer
Craig Messmer	ASHRAE, Technical Committee 8.11 (Unitary Room ACs and Heat Pumps)	Chair
Gary Rose	IntelliChoice Energy	Technician